Concluding Remarks: Dark Matter

Eric Charles (SLAC National Accelerator Lab.)

2nd World Summit on Exploring the Dark Side of the Universe
26 June 2017,
Pointe-à-Pitre, Guadeloupe

Outline

- Introduction
  - Theme: communication between communities
- A high level tour of science topics with various personal biases and a few random asides

Theme: Communicating between Communities

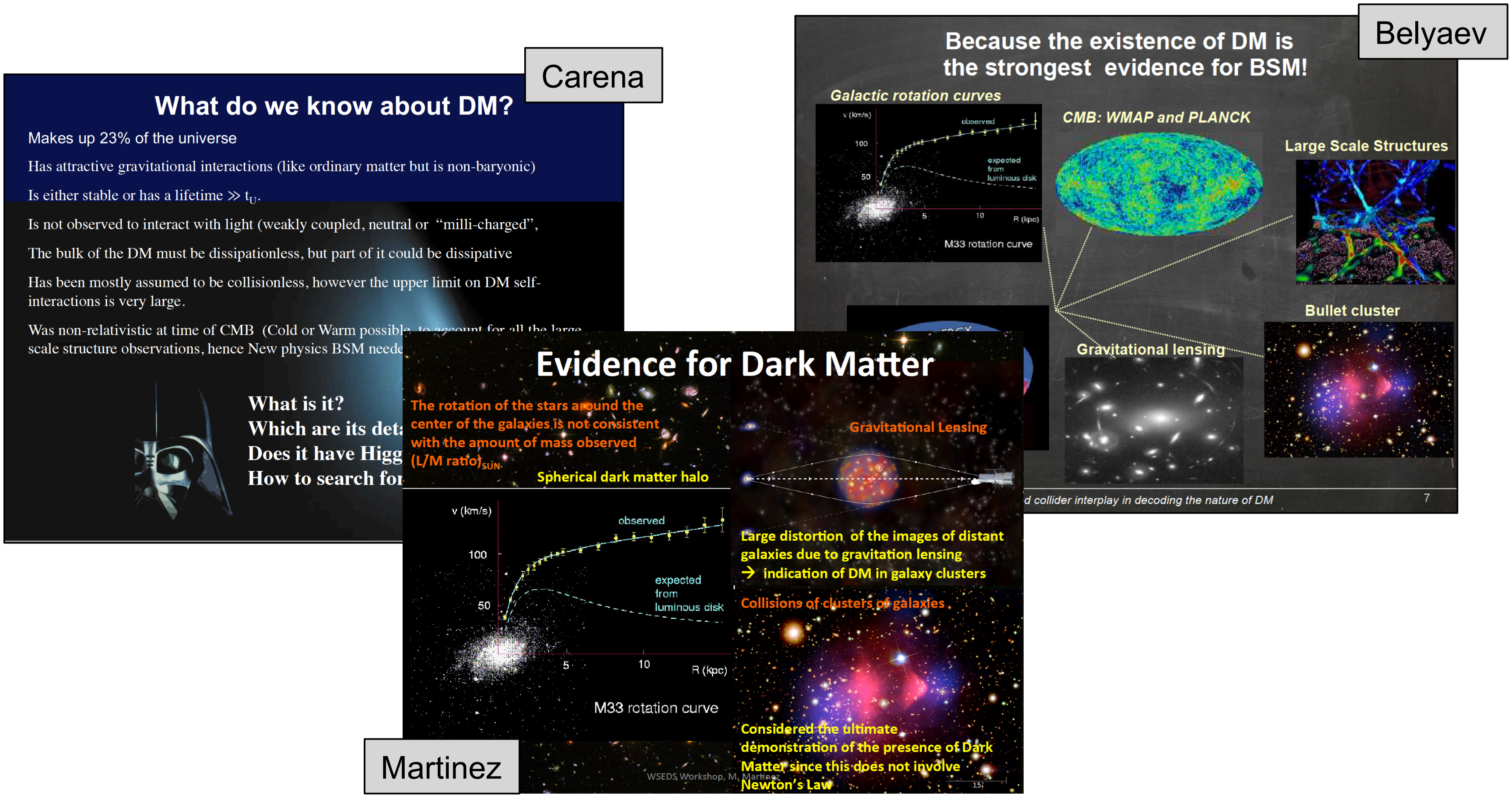
- This conference brings together people for multiple communities:
  - Accelerator-based dark matter detection
  - Direct dark matter detection
  - High-Energy Astronomy / Astrophysics
  - Cosmology
  - Neutrinos
  - Particle Theory / phenomenology
  - Black holes & gravitation
- We all had to take a step back and focus on things that will be of interest to people outside our specific communities
  - I hope this talk follows in that spirit, i.e., I'm not going to be saying a lot about nano-Bq / kg, pseudo-rapidity cuts, or γ-ray telescope instrument response functions

Topics Covered

- Dark matter theory
- Searches
  - Accelerator Based Searches
  - Direct detection
  - Indirect detection
- Cosmology & Astrophysical Dark Matter

THEORY

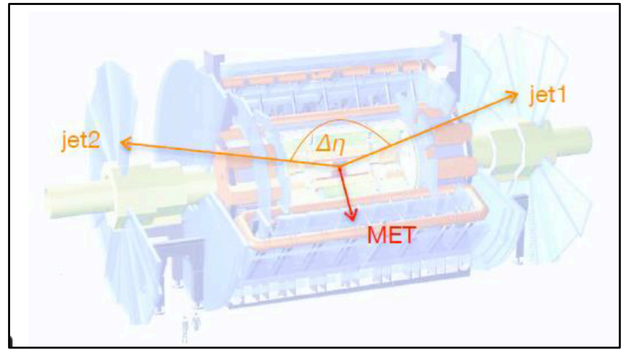
What do we know about dark matter



There is overwhelming evidence that 1) dark matter exists, and 2) it is not made of baryons.

Beyond that, we don't know much about the particle nature of dark matter

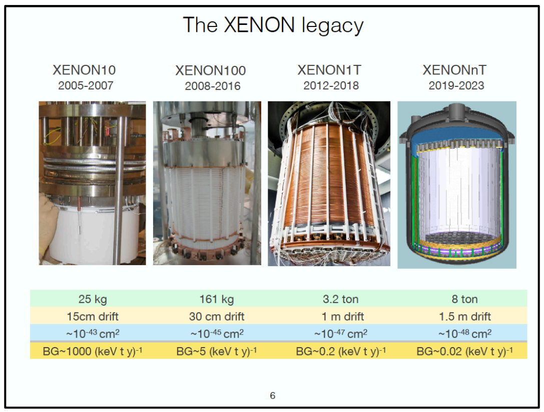
Direct, Indirect, Accelerator-based DM Searches



Martinez, Gomez-Ceballos, Dorigo, Royon, Wei, Kitali, Williams

Collider Searches

Direct Detection


The XENON legacy

XENON10 2005-2007	XENON100 2008-2016	XENON1T 2012-2018	XENONnT 2019-2023
25 kg	161 kg	3.2 ton	8 ton
15cm drift	30 cm drift	1 m drift	1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2
BG~1000 (keV t y)$^{-1}$	BG~5 (keV t y)$^{-1}$	BG~0.2 (keV t y)$^{-1}$	BG~0.02 (keV t y)$^{-1}$

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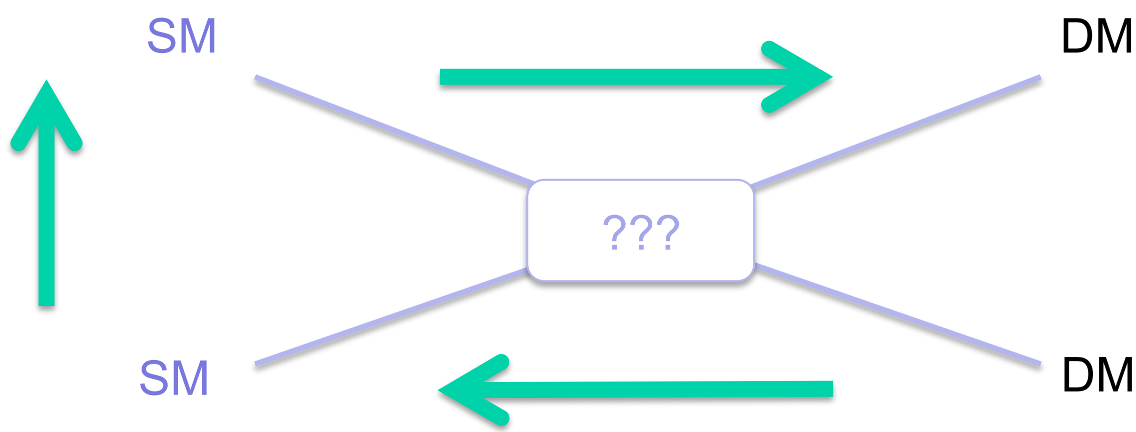
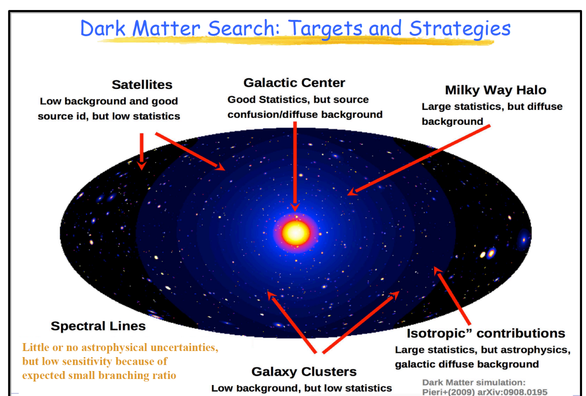
Belayaev, D'Angelo, Messina Gerbier, Kouvaris, Chevalier



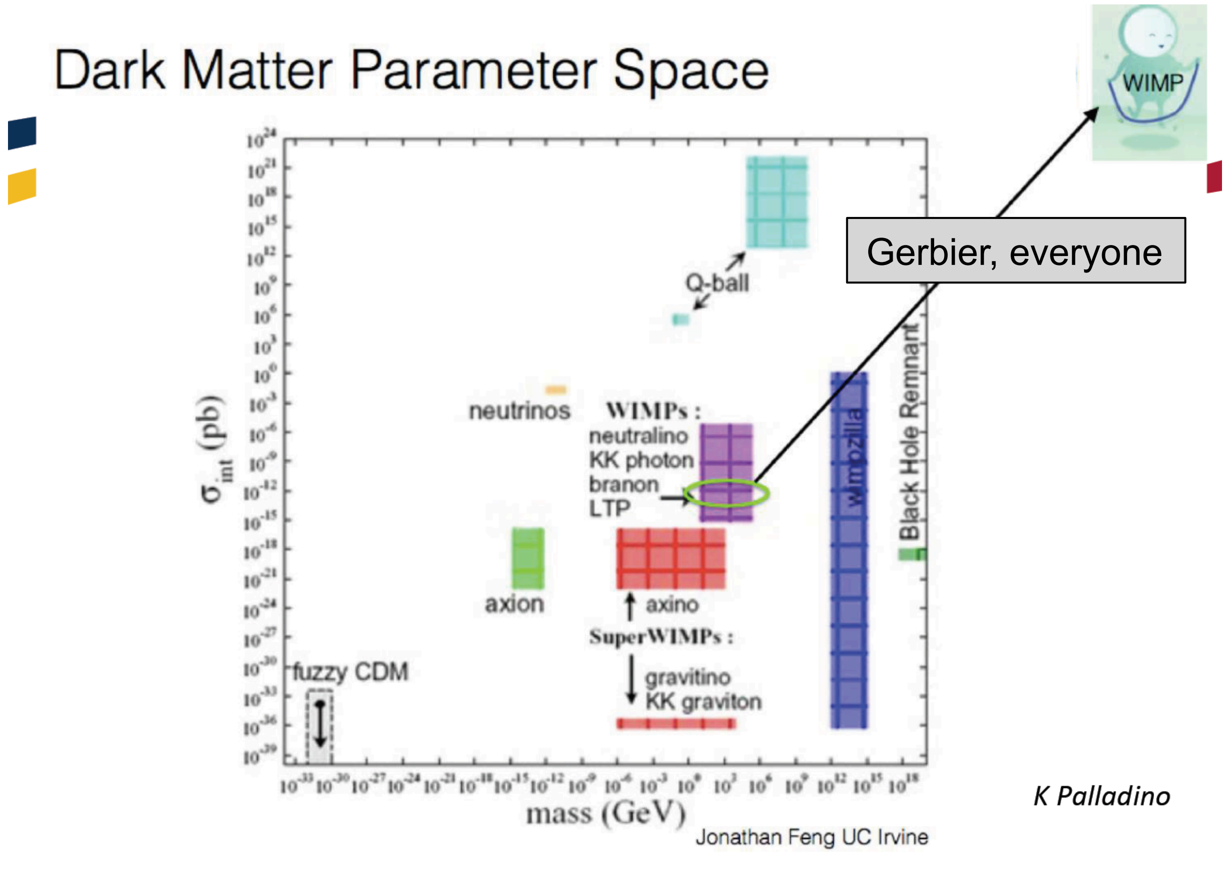
Key point: if you have a theory of the particle interactions you can predict the rates for all of these processes, ***and translate results between communities***.



Morselli, Vincent, Humensky, Charles, Gormez-Vargas, Aguilar

Indirect detection

Dark Matter Parameter space: lamppost physics



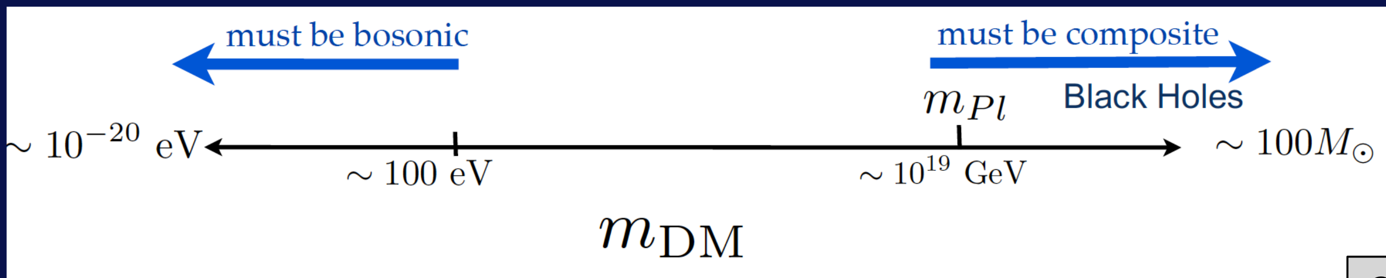
This figure showed up in several talks. Interestingly, it was typically followed by an explanation of why the speaker was going to focus on WIMPs (or in a few cases, axions or primordial black holes).

Kouvaris, Chevalier, Williams

Garcia-Bellido, Vidotto

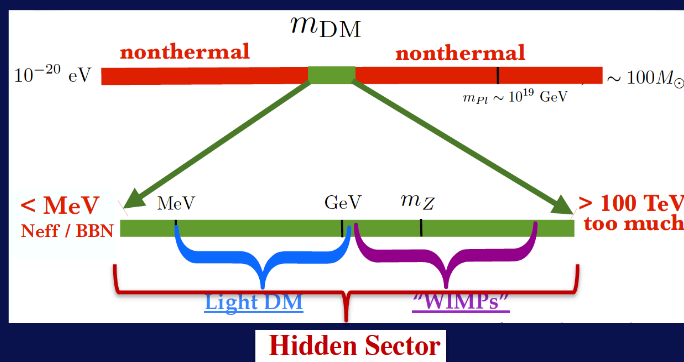
What types of theories are we looking at?

Particle physics properties constrains the range of possible masses

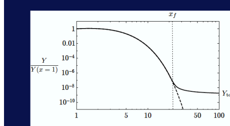


Carena

Thermal Equilibrium:
Narrows viable Mass range



The WIMP Miracle



Taking $x_f \sim 10$ and $\langle\sigma v\rangle \sim \alpha^2/m^2$, the fraction of critical density contributed by the DM today is

$$\Omega_\chi h^2 \sim (10^{-26} cm^3/s)/\langle\sigma v\rangle \simeq 0.1\ (0.01/\alpha)^2\ (m/100\ GeV)^2$$

➔ correct abundance today as measured by Planck and WMAP, for $\alpha \sim 0.01$ and $m \sim 100$ GeV

the "WIMP miracle"

Weak-scale DM naturally gives the correct DM density
Many well-motivated BSM models contain a parity symmetry
SM → SM BSM → - BSM

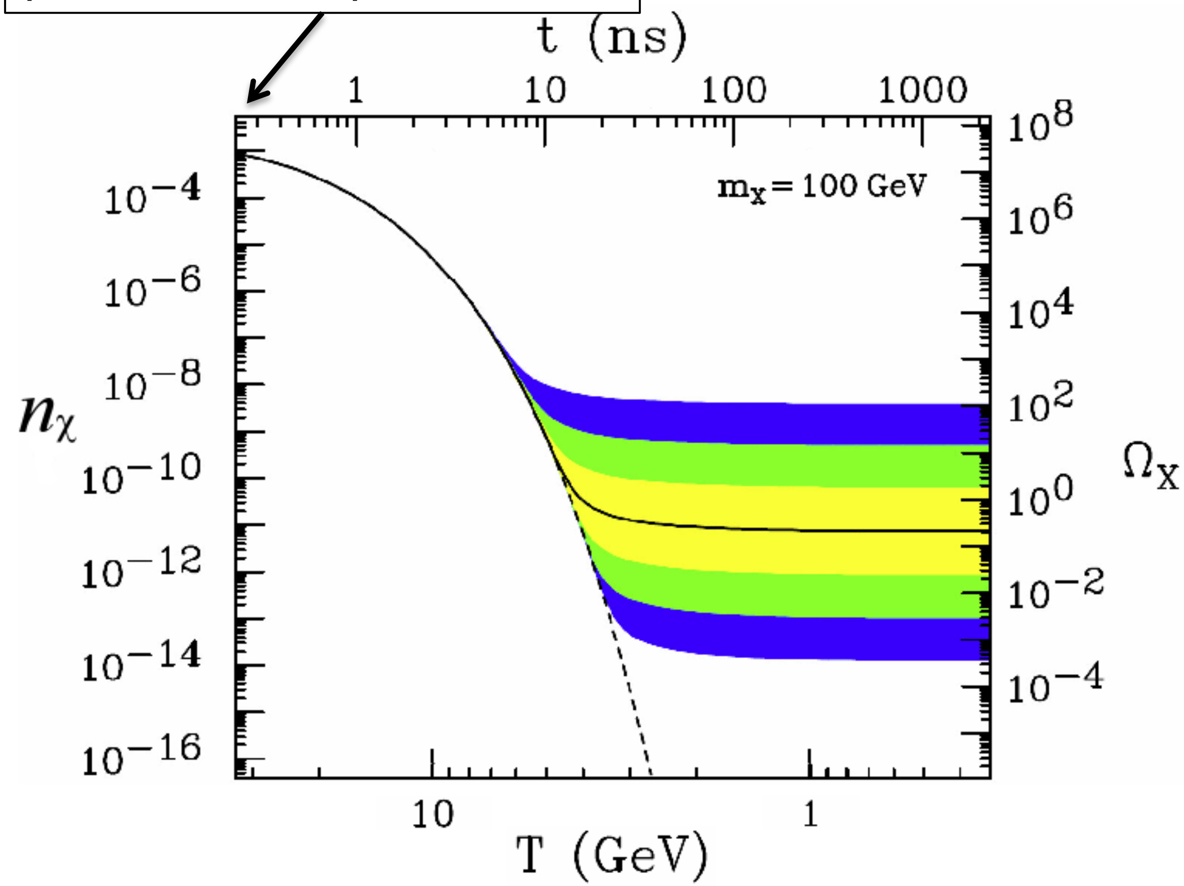
e.g. R-parity in SUSY (proton decay)
T-parity in little Higgs models (precision EW observables)
KK-parity in extra-dimensional models .....

Lightest **P**arity **O**dd **P**article is stable, may be a DM candidate
Always produced in pairs and leaves detector as MET
A wide-ranging of experimental programs targeted for WIMP searches

"Good news: Most discoverable DM candidates are in Thermal equilibrium with us in the early universe" – Marcela Carena

Aside: Dark Matter as a Thermal Relic

1. For the first 0.1 ns of the Universe it is hot enough to produce exotic particles.



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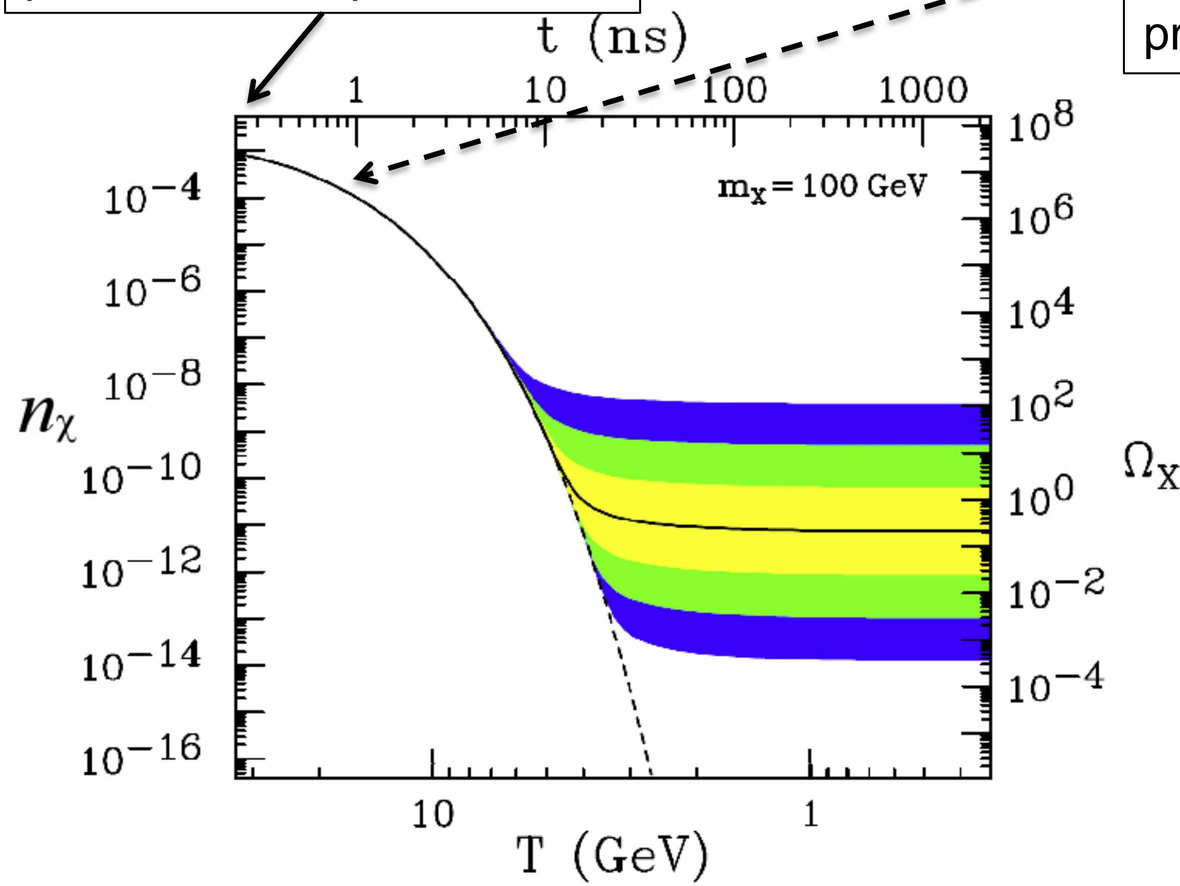
1. For the first 0.1 ns of the Universe it is hot enough to produce exotic particles

2. After about 0.1 ns, the Universe has cooled enough that exotic particles are no longer produced, but can annihilate.



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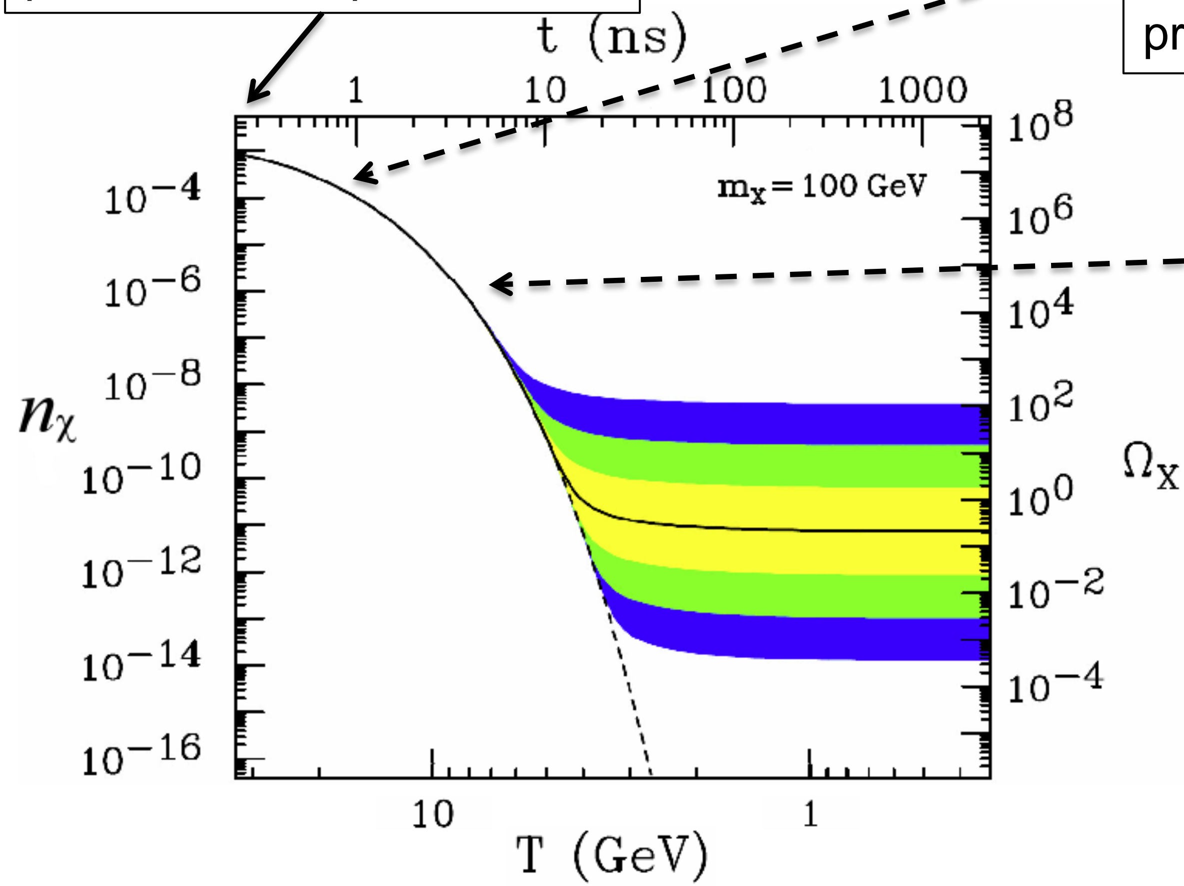
2. After about 0.1 ns, the Universe has cooled enough that exotic particles are no longer produced, but can annihilate.

3. For about 10 ns, the density is so high that almost all the exotic particles do annihilate.



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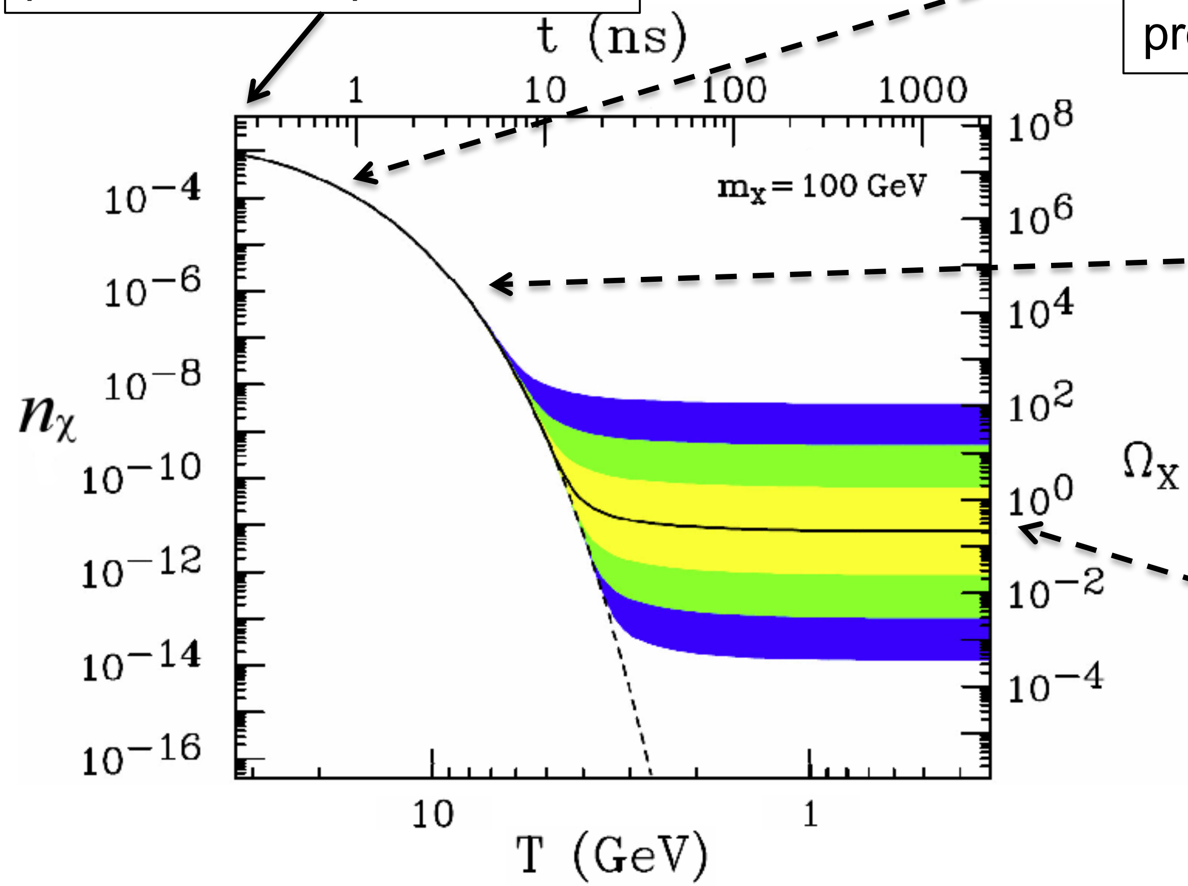
4. Only about 1 in 100 Billion of the exotic particles survive, these account for all the dark matter that exists today.



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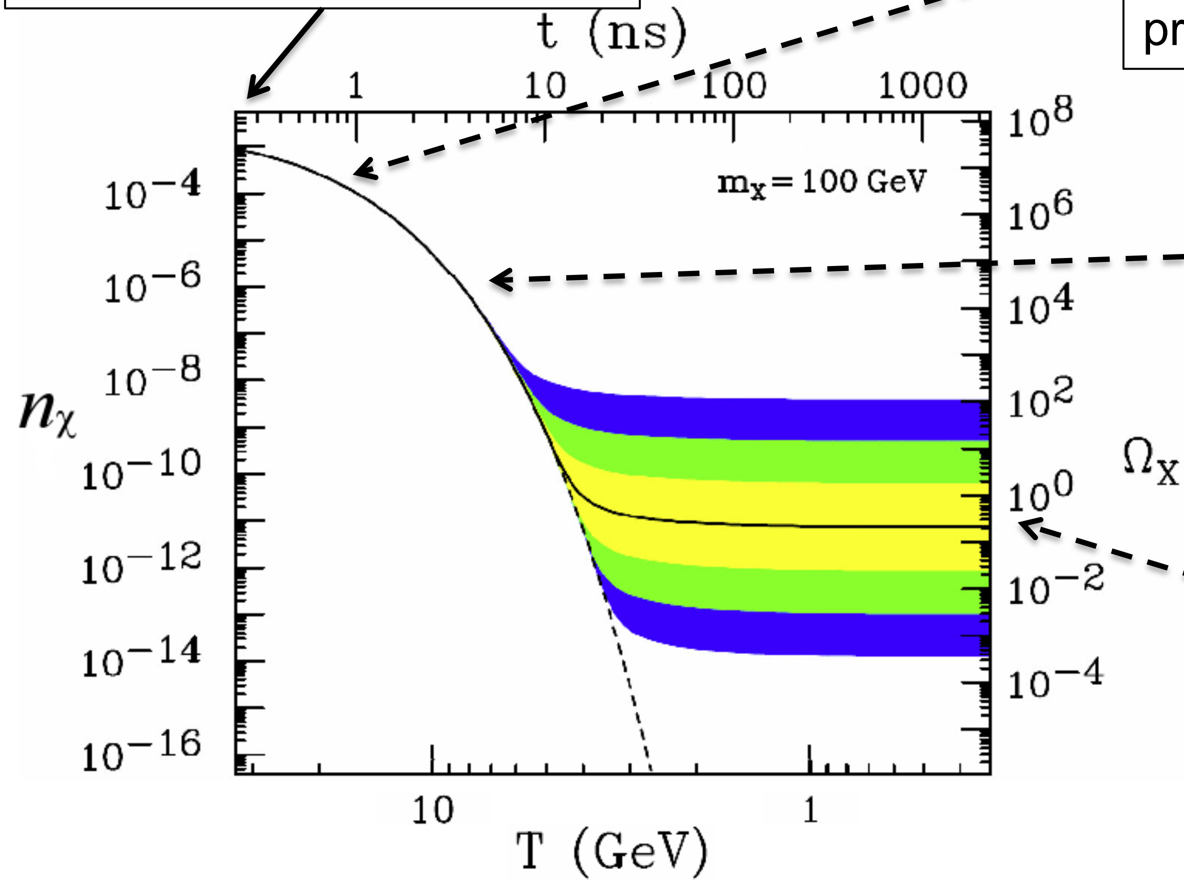

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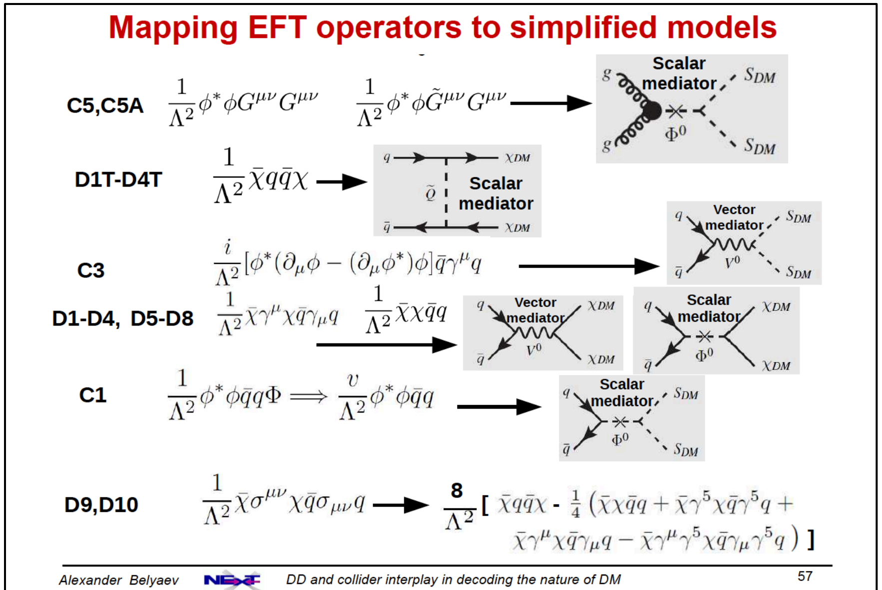
4. Only about 1 in 100 Billion of the exotic particles survive, these account for all the dark matter that exists today.

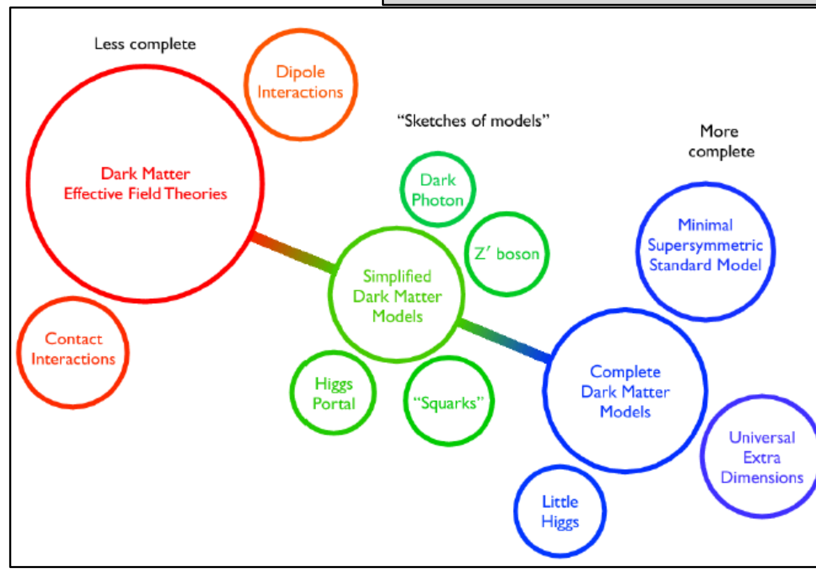
5. The surviving fraction depends critically on the annihilation cross section (i.e., probability): small differences would yield very different dark matter densities today.

DM Theory Space is Vast and Diverse



Belayaev

Belayaev, Carena, LHC talks

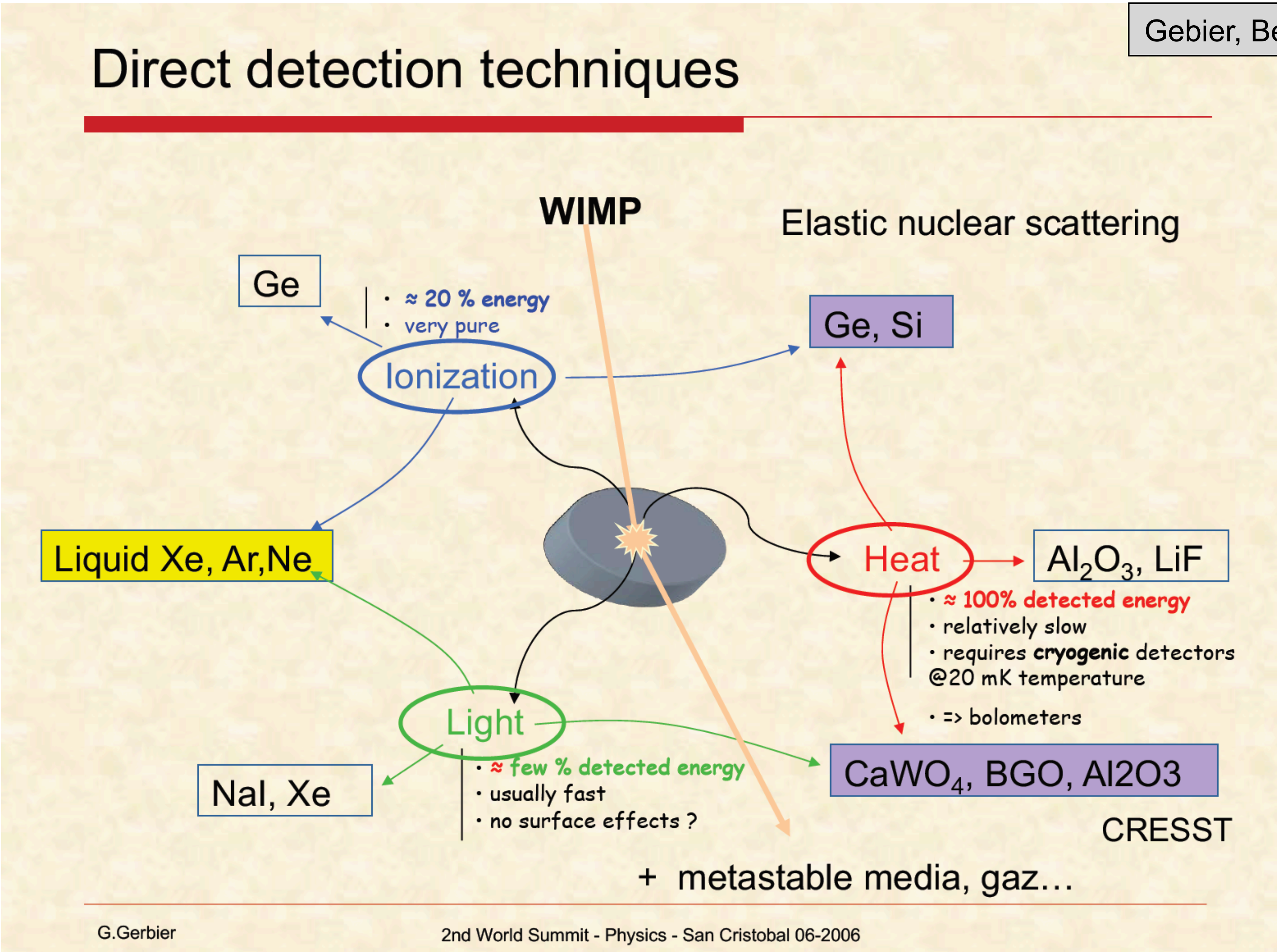


Key point: theory space is huge, some amount of simplification & organization is needed to approach the problem in a sensible fashion

DIRECT DETECTION

Direct Detection Techniques

Gebier, Belayaev



DM Scattering Produces Heat, Light & Ions

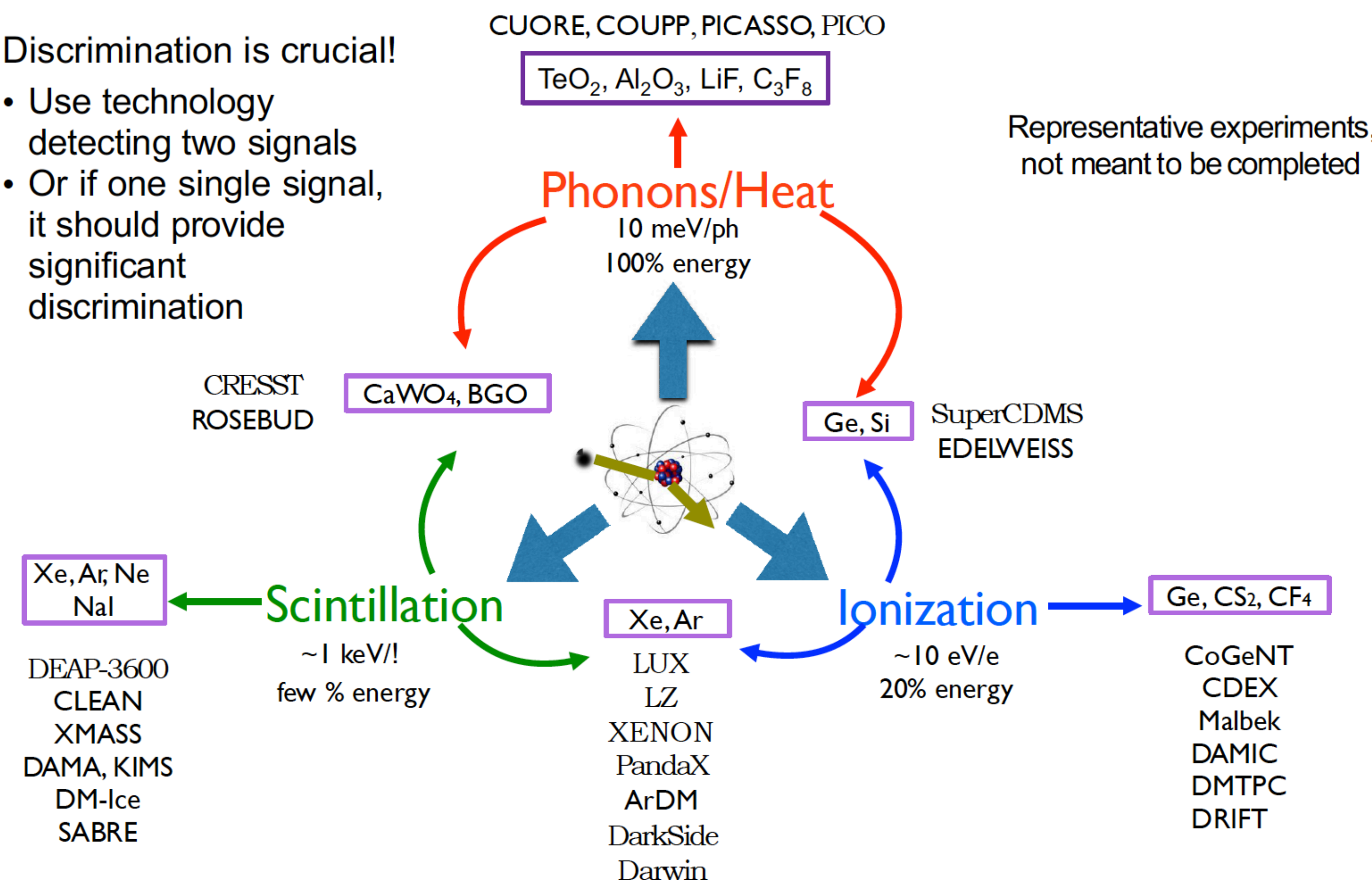
Masbou, EDU 2017
Recontres de Viet Nam

Direct Detection Techniques

from Carmen Carmona

Discrimination is crucial!

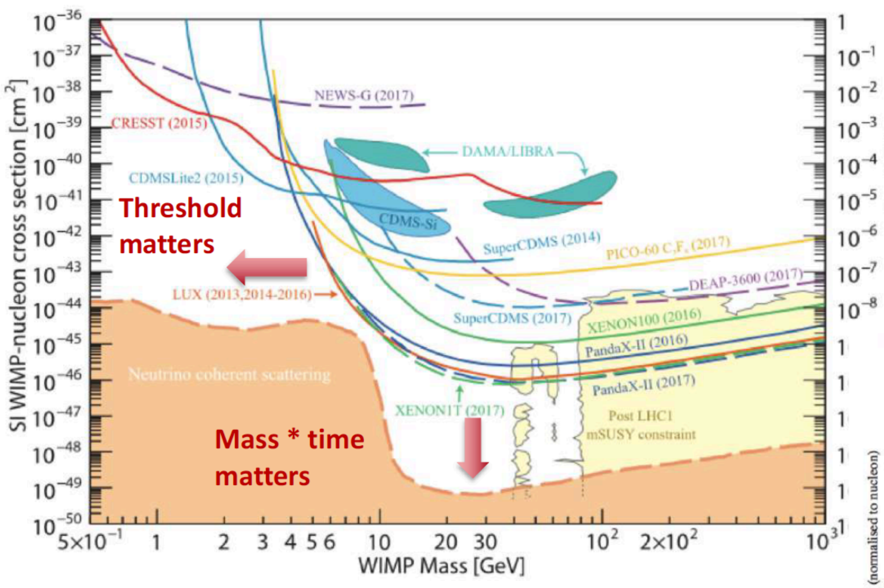
- Use technology detecting two signals
- Or if one single signal, it should provide significant discrimination



One slide summary of Direct Detection Status

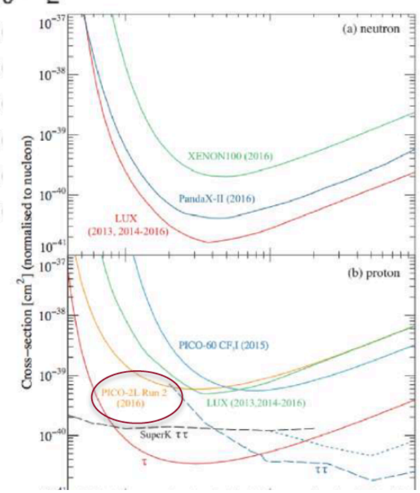
Now : actual results (RPP/PDG, Dark Matter review 2018)

Gebier



Spin independent couplings

Spin dependent couplings



E.A. Bagnaschi *et al.*, Eur. Phys. J. **C75**, 500 (2015).

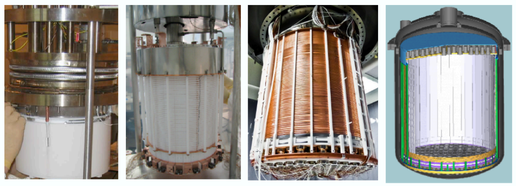
CMSSM, NUHM1, NUHM2, pMSSM10

Direct detection of WIMPs: > 10 GeV focus is on making larger volumes with low backgrounds, < few GeV focus is on lowering effective thresold

Also, cottage industry in understanding the DAMA/Libra results

High-mass DM, Xenon 1T Results

The XENON legacy



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BG~1000 (keV t y)$^{-1}$	BG~5 (keV t y)$^{-1}$	BG~0.2 (keV t y)$^{-1}$	BG~0.02 (keV t y)$^{-1}$

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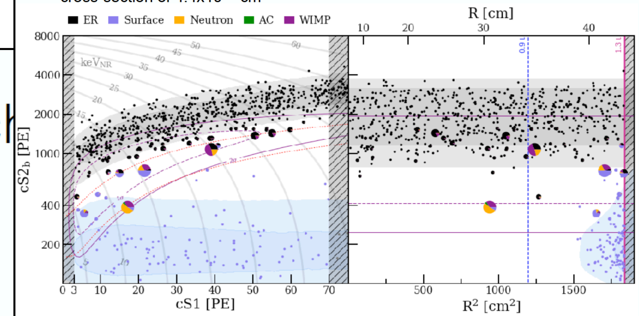
Dark Matter Search Results

- Results interpreted with un-binned profile likelihood analysis in cs1, cs2, R, z space
- piechart indicate the relative PDF from the best fit of 200 GeV/c² WIMPs with a cross-section of 4.4x10^{-47} cm²



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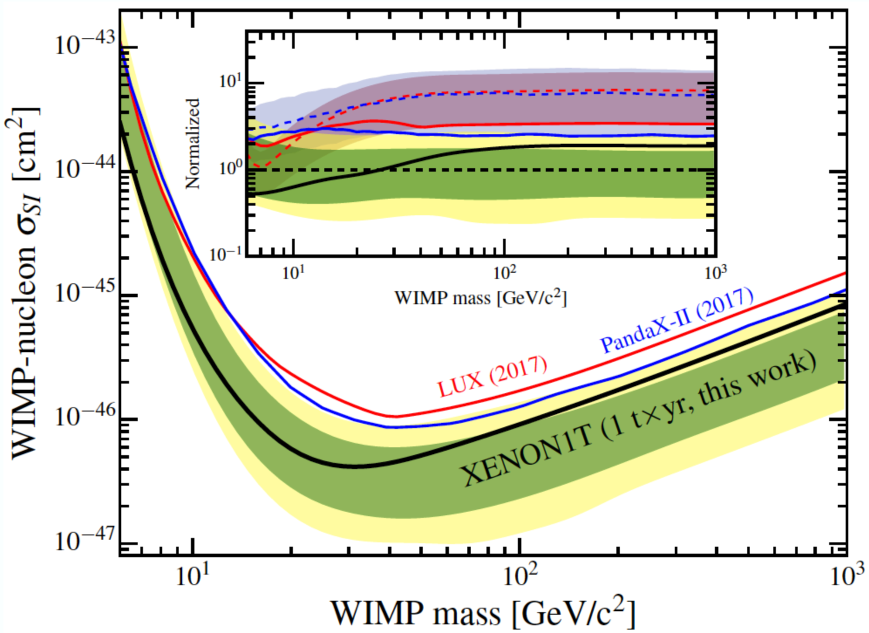
1T Dark Matter Search



- Most stringent 90% CL upper limit on WIMP-nucleon cross section above 6 GeV
- Factor of 7 more sensitivity compared to previous experiments
- ~ 1sigma upper fluctuation from median sensitivity

Minimum at 4.1x10^{-47} cm² for a WIMP of 30 GeV/c²

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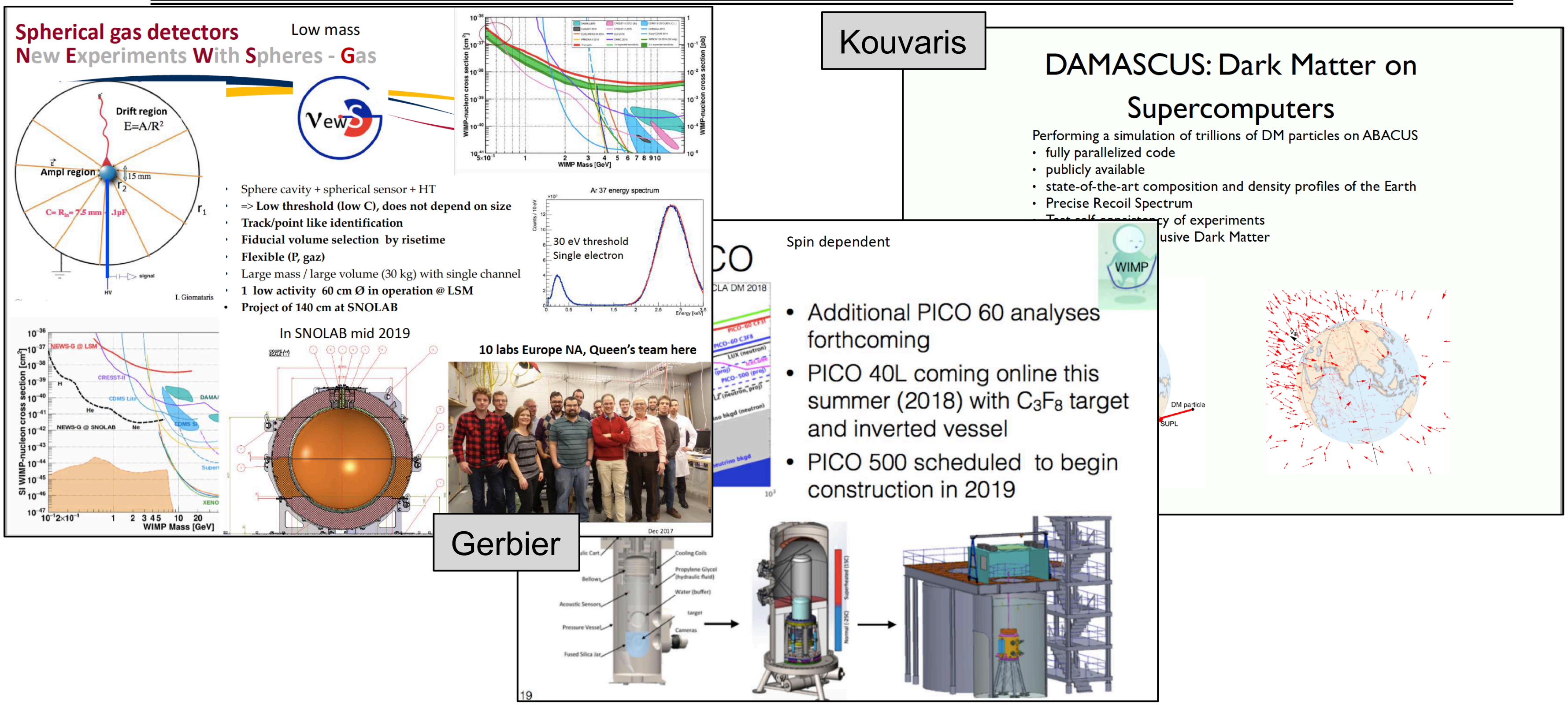
Messina

Low mass WIMPs, pushing down the threshold, reducing background



Many developments in searching for low mass WIMPs:

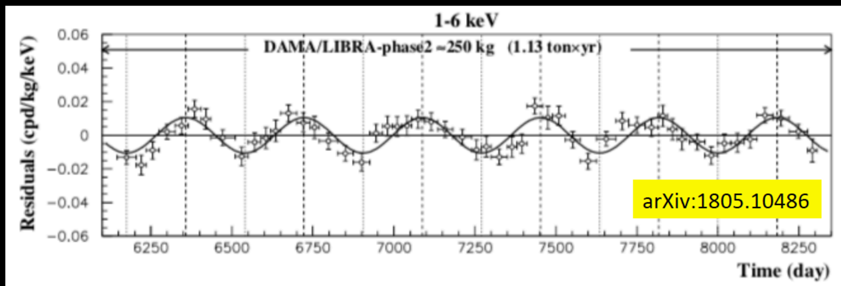
New target materials

Using modulation signals to reduce noise

Directional direction

Reproducing the DAMA / LIBRA results

…and now including DAMA/LIBRA-Phase2



- 20 annual cycles (DAMA/NaI + DAMA/LIBRA-Phase1 + DAMA/LIBRA-Phase2)
- Exposure: 2.46 ton x yr
- χ^2/ndf = 150/52 (Ph2-only 1-6keV); 199/102 (Ph1+Ph2 2-6keV)
- 12.9σ significance
- (0.999±0.001) year period
- Phase is (145±5) days vs. Exp. DM phase 152.5 days
- Amplitude: (0.0103±0.0008) cdp/kg/keV, i.e. ~ 1% of the experimental rate.

EDSU 2018 D. D'Angelo - DM Modulation 9

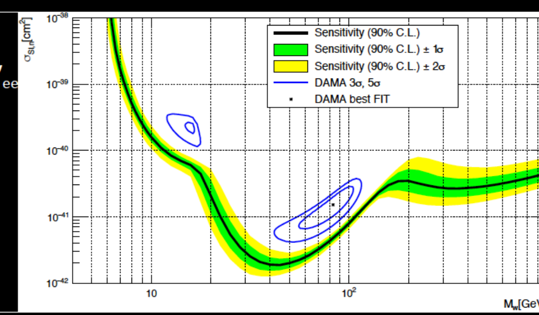
d'Angelo

SABRE Sensitivity

arXiv:1806.09340

1. Model-independent approach: 50k toy-MC data sets with/without signal yield 6σ/5σ power to verify/refute the claim at 90% C.L.
2. Classic sensitivity curve to SI WIMP-nucleon interaction

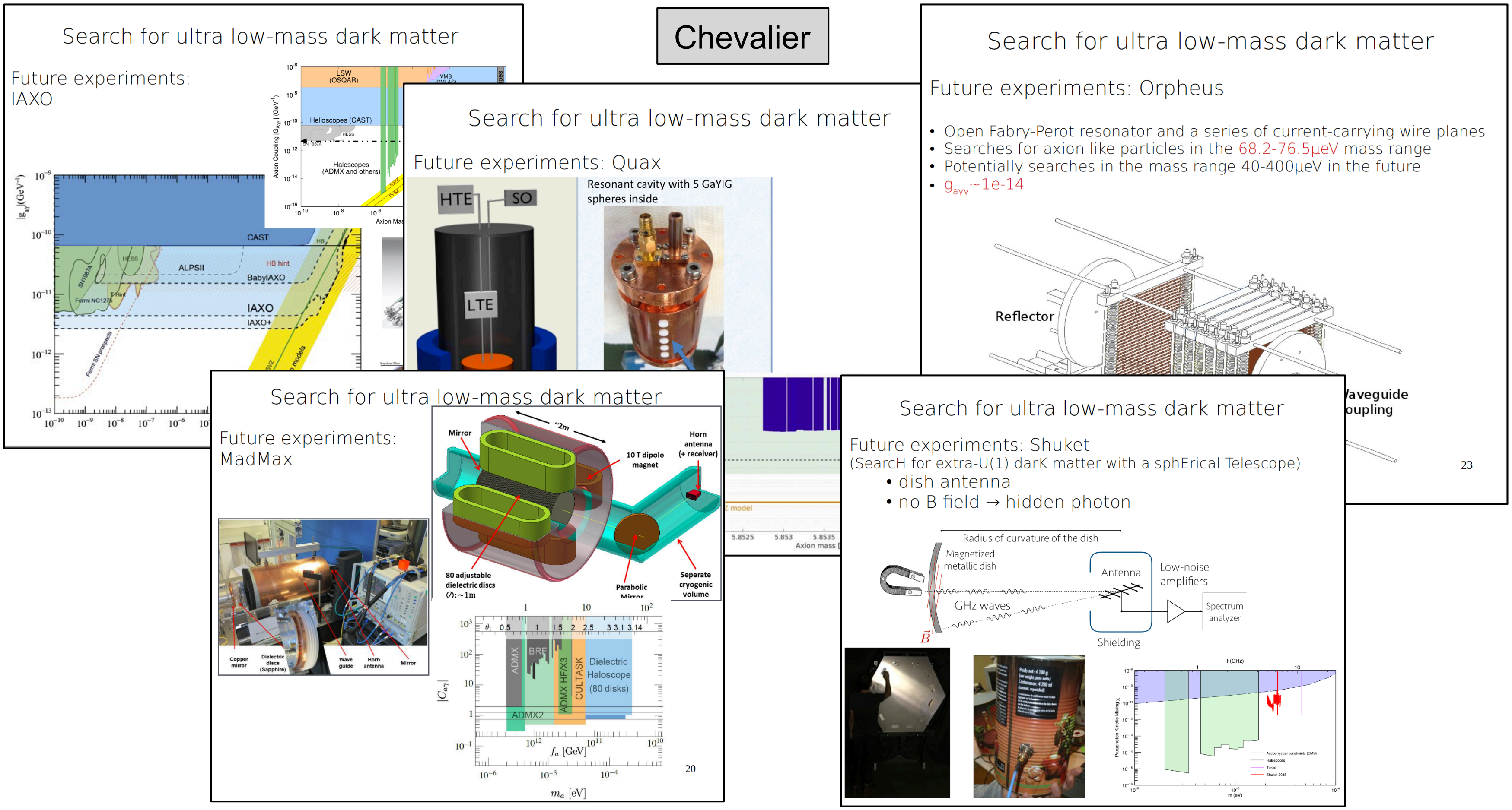
Exposure: 50 kg x 3 yr
Background: 0.22 cpd/kg/keV$_{ee}$
Quenching: Xu et al. PR C92 (2015) 015807.
Systematics: quenching, resolution, efficiency, background
DAMA islands: Phase1 only



EDSU 2018 D. D'Angelo - DM Modulation 33

Several experiments coming online to attempt to reproduce DAMA / Libra result as closely as possible. Approaching required sensitivity.

Direct Detection of Axions / Ultra Light Dark Matter

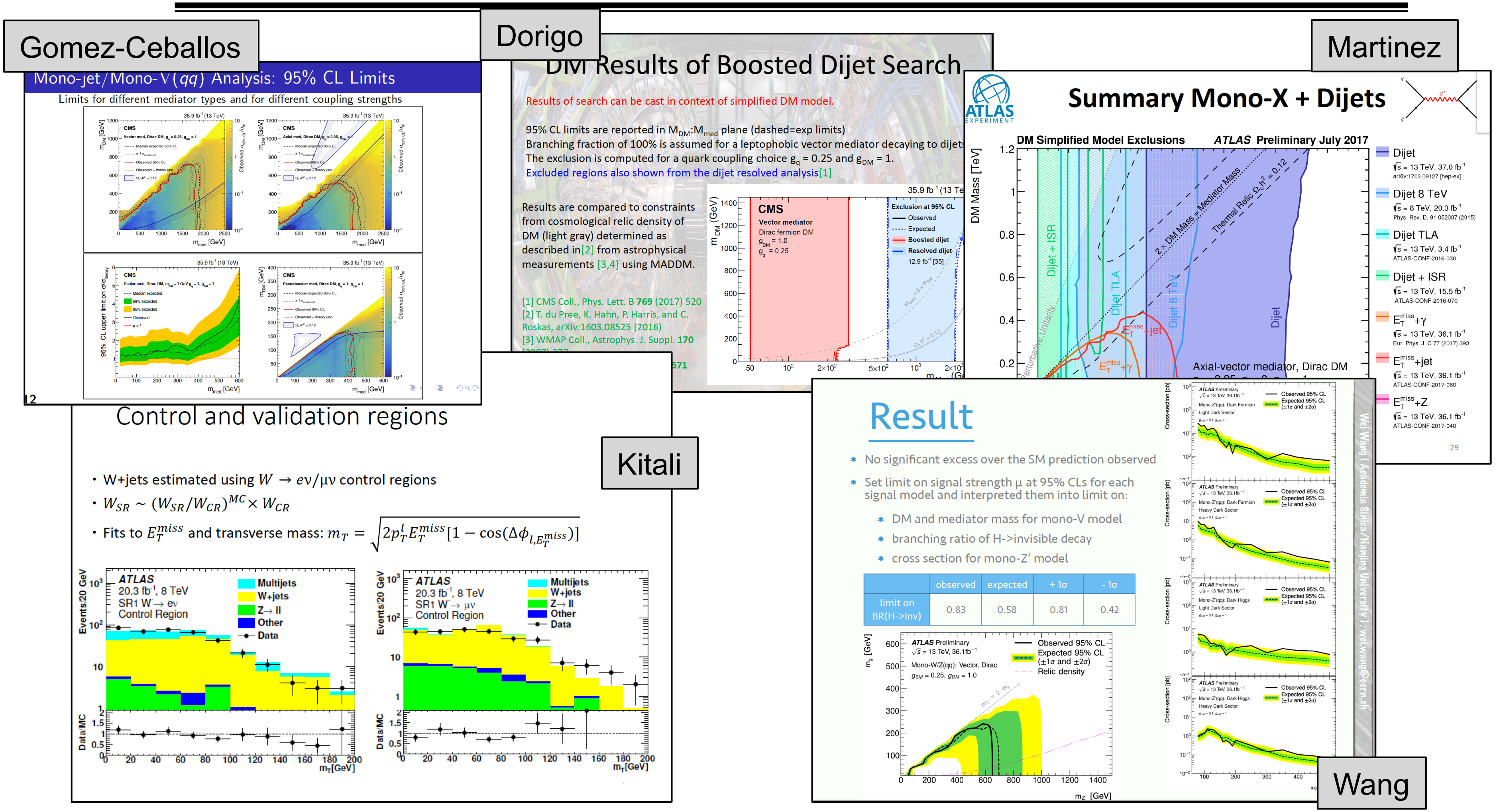


Several experiments coming online to look for ultra low mass DM

Key point: ultra low-mass DM is bosonic, and acts more as a field than as particle.   Look for SM particle coupling to field.

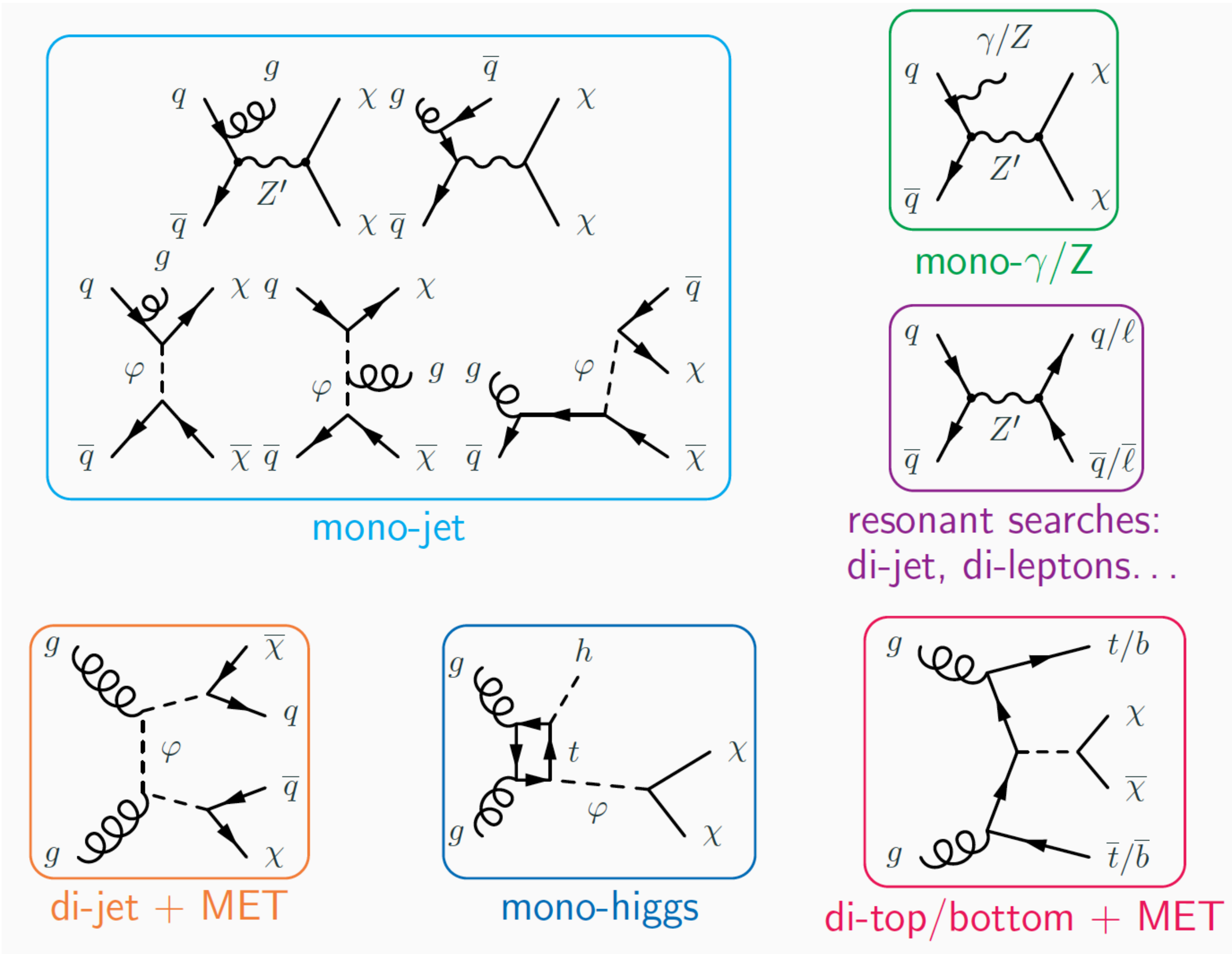
ACCELERATOR SEARCHES

Searches for DM Candidates at the LHC

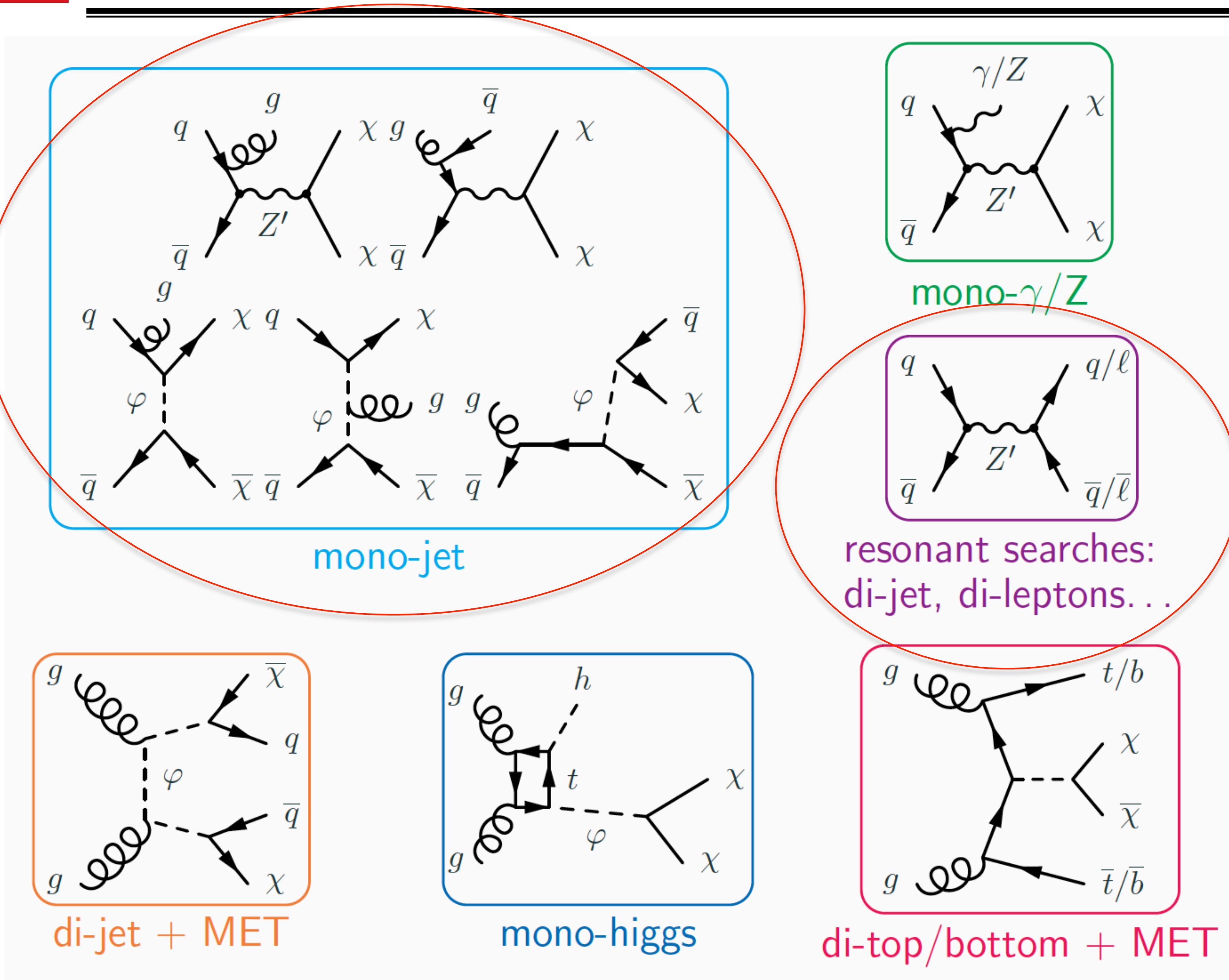


- Several talks about searches for different topological signatures at the LHC
- As an outsider, biggest questions are: how they all tie together, and what are the implications for WIMPs as DM

Event topologies



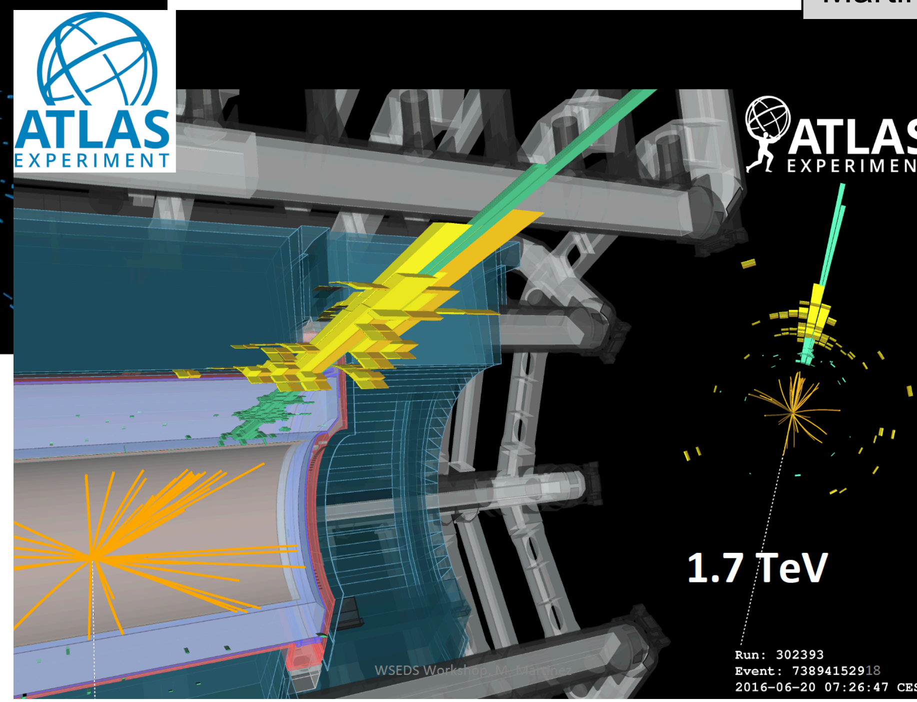
Event topologies



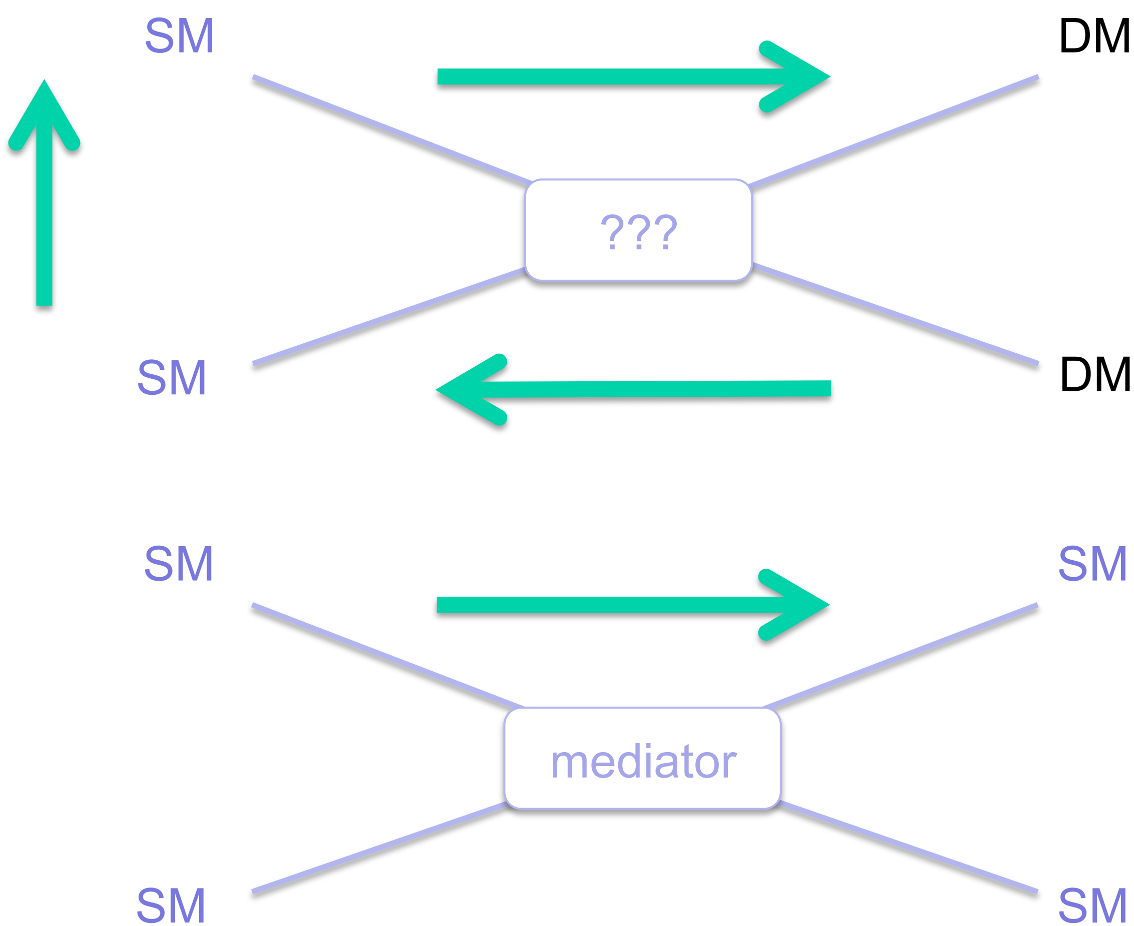
Event Topologies

Dorigo

Martinez

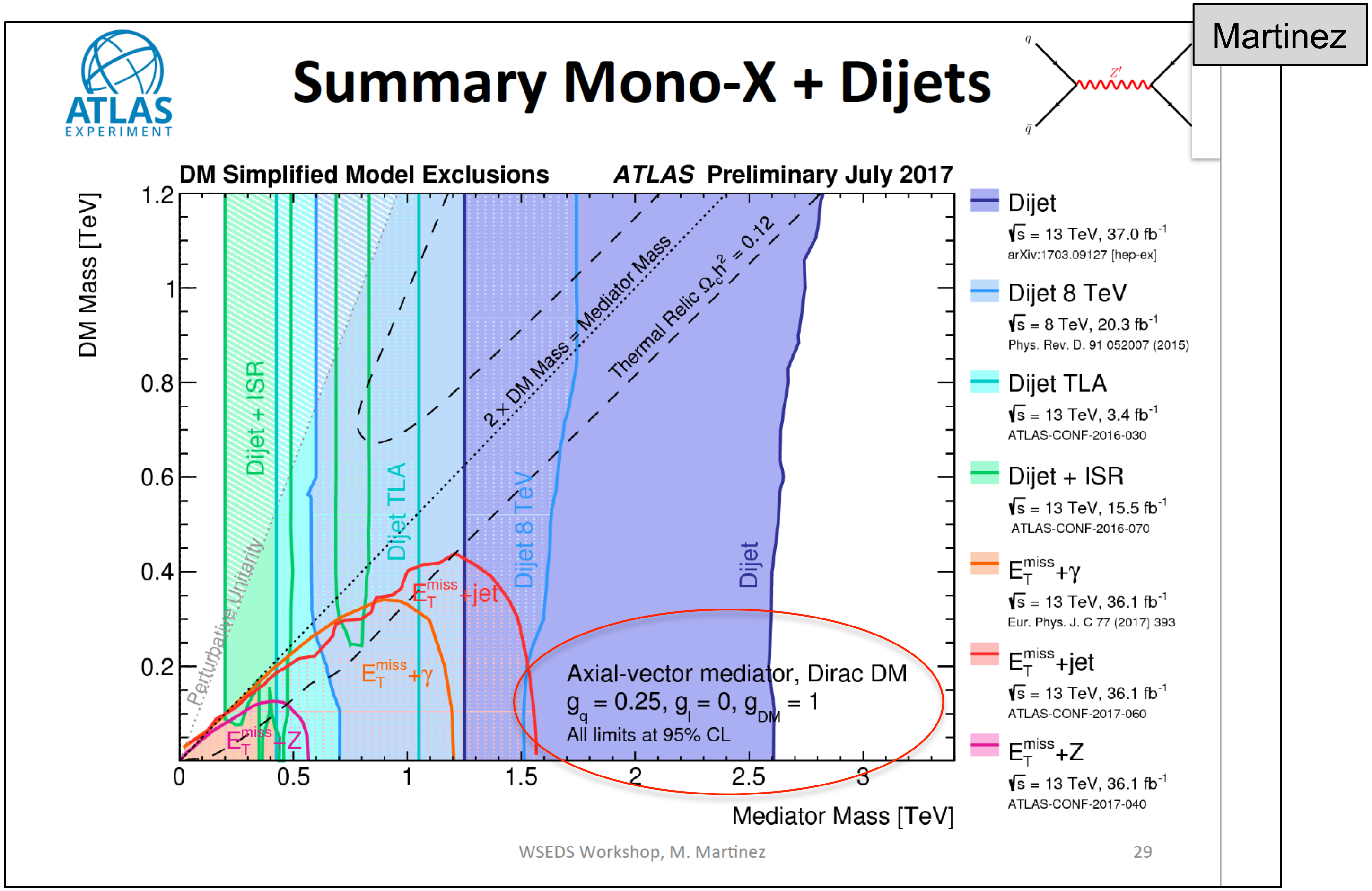


What's missing in the complementarity diagram



- Important point: for many models, the strongest constraint on thermal DM comes from searches for the mediator, i.e., di-jet searches.

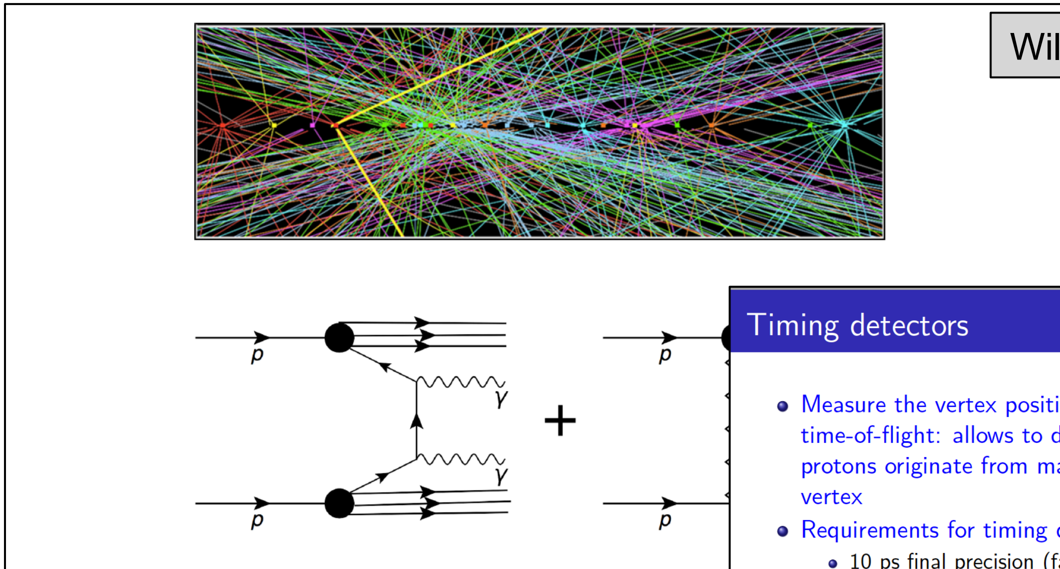
DM Implications of LHC Searches



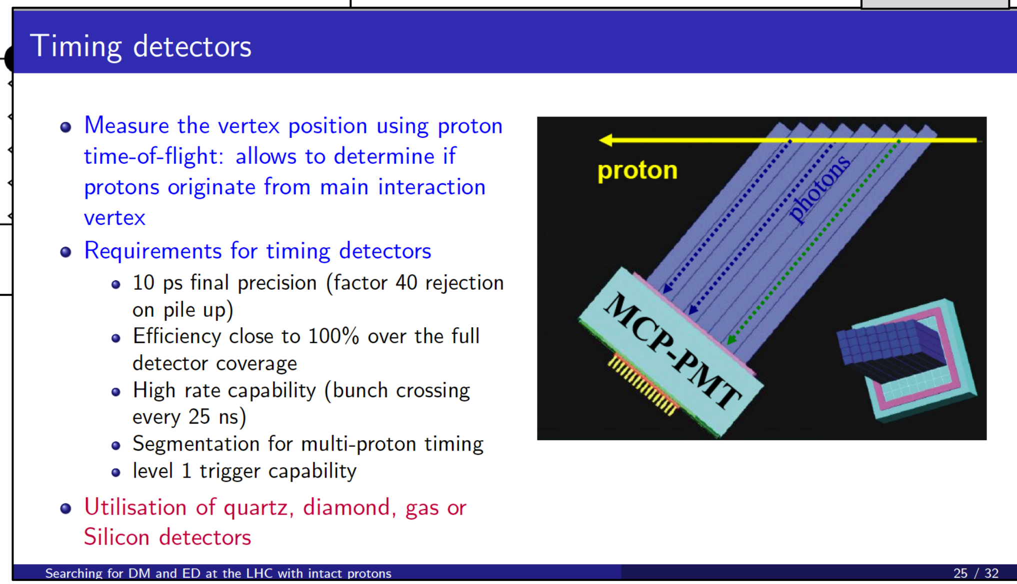
- Mono-jet search (red) looks for missing transverse energy from DM particle but is limited by high missing energy cut need to reduce background
- Di-jet search (blue) looks for DM mediator particle producing pairs of SM particles and can reach higher energies

Non-WIMP Accelerator Searches

Williams



Royon



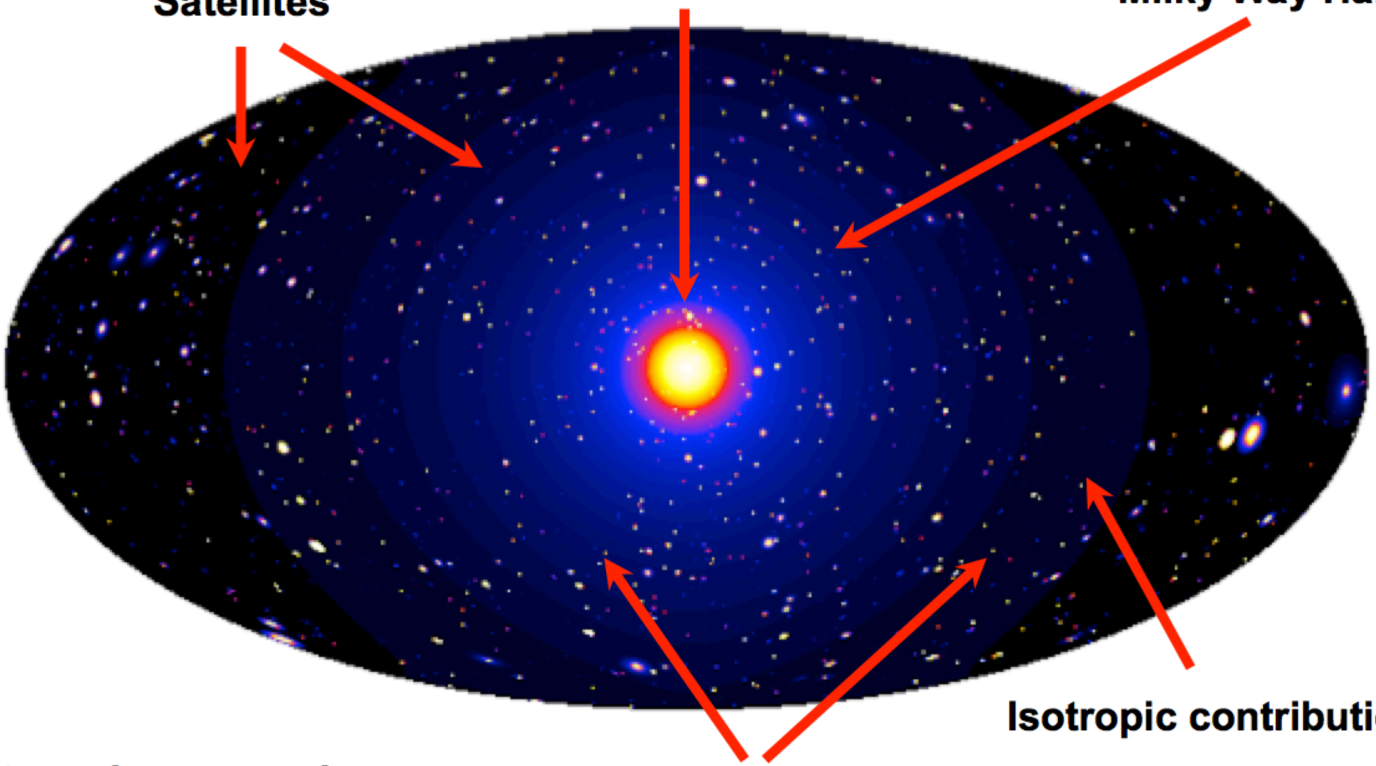
Searching for anomalies in the proton scattering near the LHC beamline caused by new operators.

Technical challenge, reducing the beam backgrounds, requires amazing time resolution (~10 ps)

INDIRECT DETECTION

What signal would DM annihilation to γ-rays make?

Dark Matter as Seen From Earth



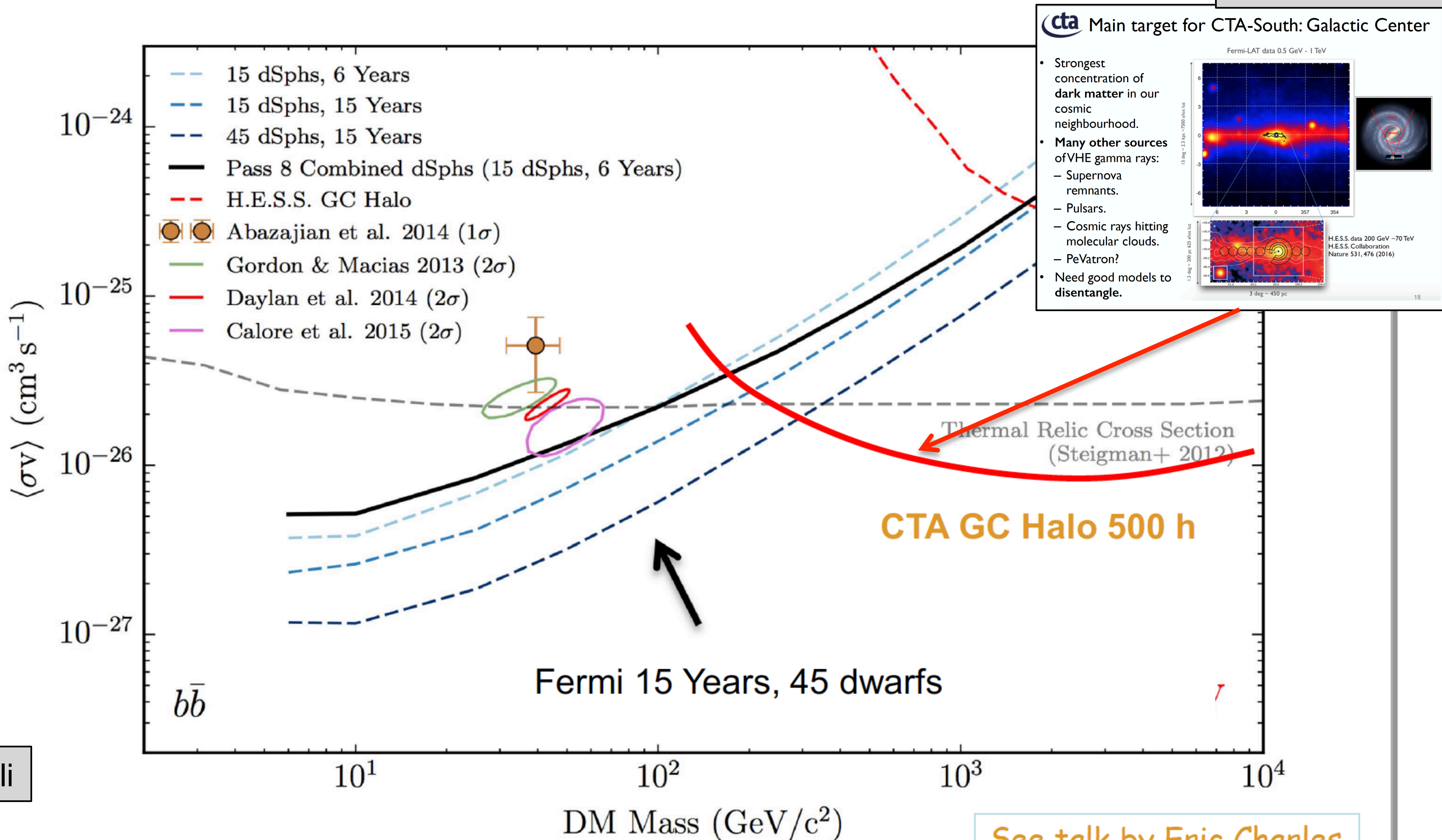
Features in γ-ray and cosmic-ray spectra

Dark Matter simulation: Pieri+ (2011)

Summary of Indirect Detection Searches

DM limit improvement estimate in 15 years (2008- 2023)

Gomez-Vargas



Morselli

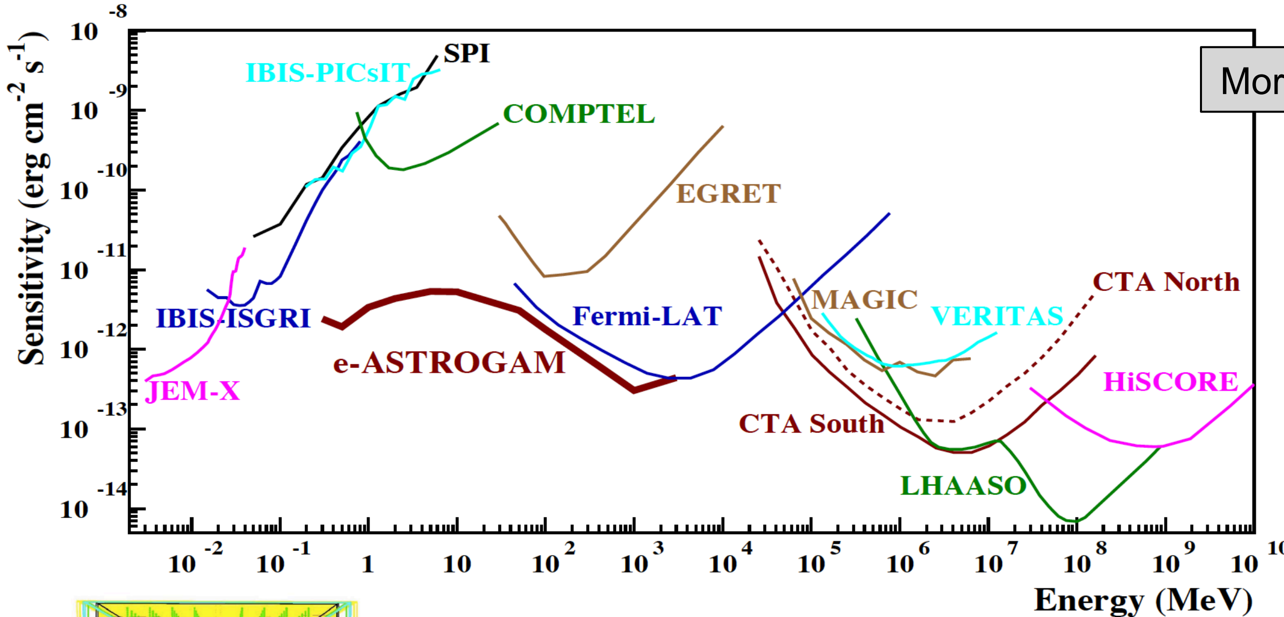
See talk by Eric Charles

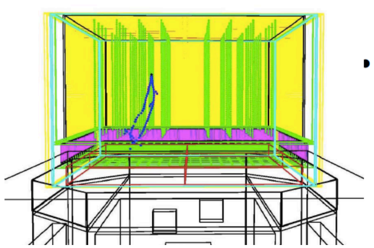
Together Fermi and CTA will probe most of the space of WIMP models with thermal relic annihilation cross section

The unexplored MeV energy band

e-ASTROGAM Performance assessment

Morselli





- e-ASTROGAM performance evaluated with **MEGAlib** and – both tools based on Geant4 – and a detailed numerical mass model of the gamma-ray instrument

e-Astrogam: arXiv:1611.02232

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Great science case for MeV mission, current designs are 100x more sensitive than COMPTEL.

Such missions would be sensitive to low-mass WIMPs

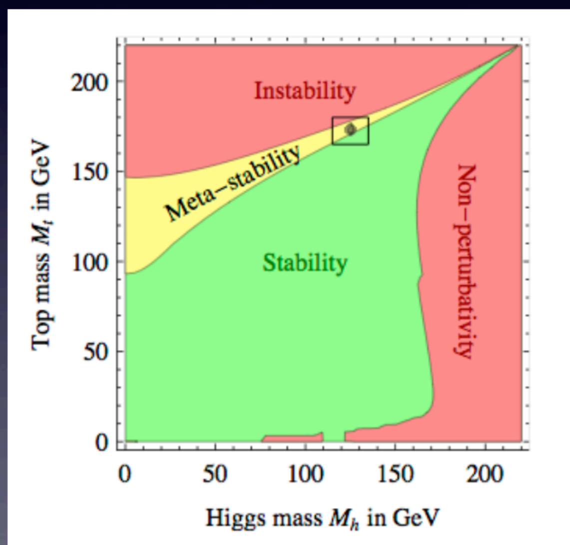
Cosmology & Astrophysical Dark Matter

Inferred DM constraints

Moss

Stability regions*

$O(\hbar^2)$



The potential depends on the Higgs and Top mass

$$V_{\mathrm{eff}} = \frac{1}{4}\lambda_{\mathrm{eff}}(\phi)\phi^4$$

where

$$\frac{d\lambda_{\mathrm{eff}}}{d\ln\phi} = \beta_\lambda - 4\gamma\lambda_{\mathrm{eff}}$$

*Degrassi et al arXiv:1205.6497

"There is observational evidence that the false vacuum has not decayed by seeded nucleation" -> no PBHs below 10^{15}g

Recent "excesses/anomalies"

Vincent

3.5 keV line
21 cm (EDGES)
AMS-02 antiprotons
PAMELA/AMS positron
Galactic centre GeV excess
Solar composition problem
White dwarf cooling anomaly
…

⇒

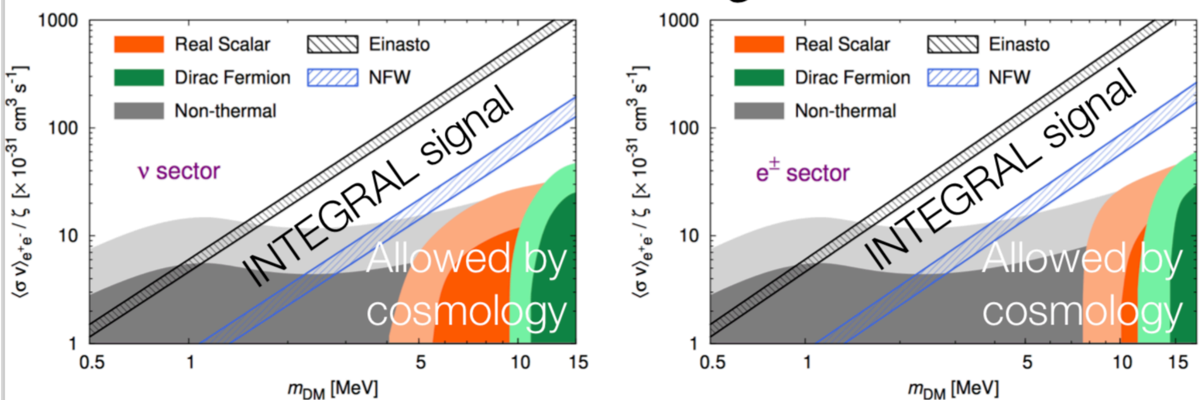
need strong corroboration because astrophysics is not a controlled setting: backgrounds are difficult to model

Vincent

Complete constraints on a WIMP origin of 511 keV

Thanks to Planck-provided **likelihoods**, can MCMC:

ν $e^{\pm}$



WIMP scenario seems disfavoured

Wilkinson… AV 2016

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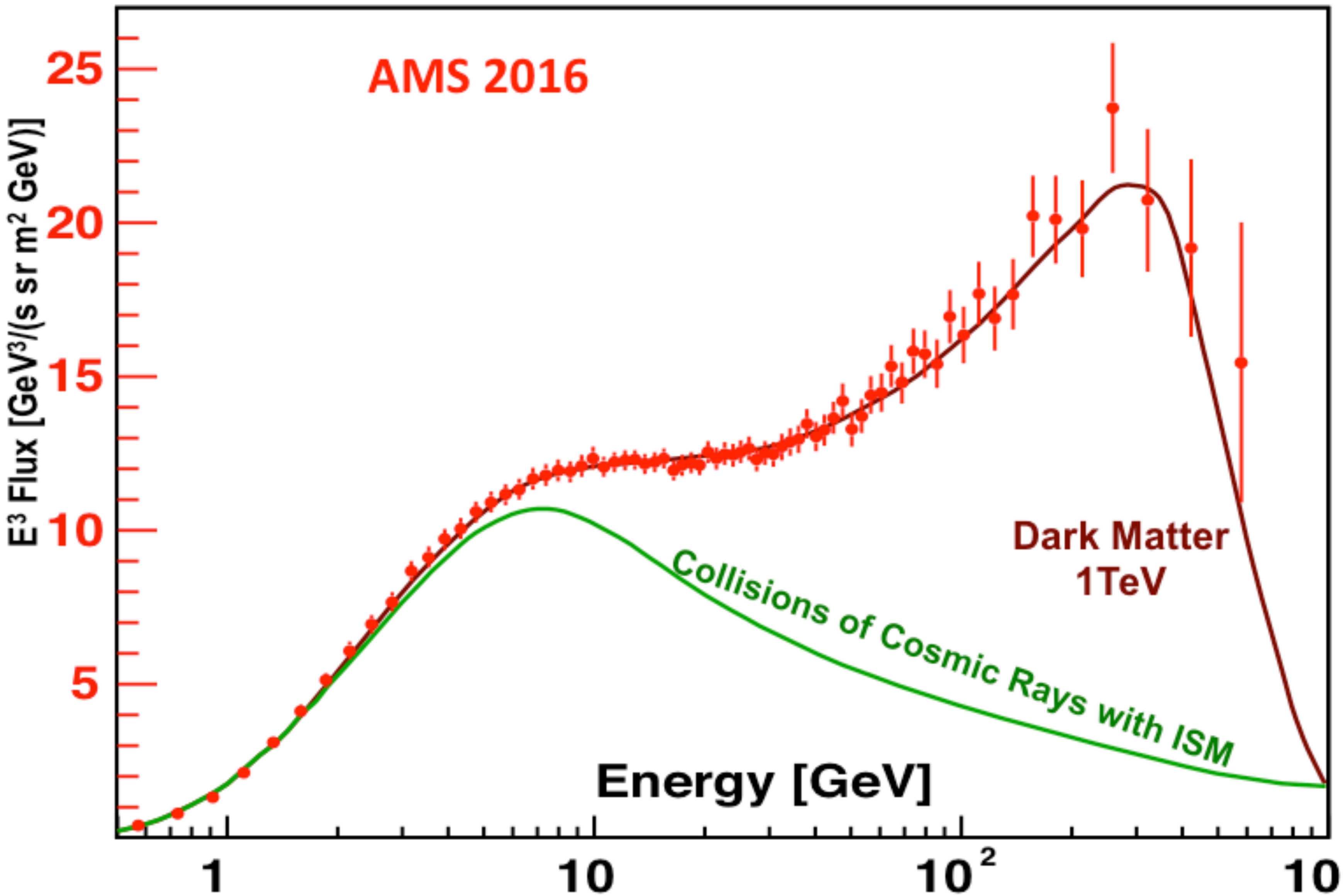
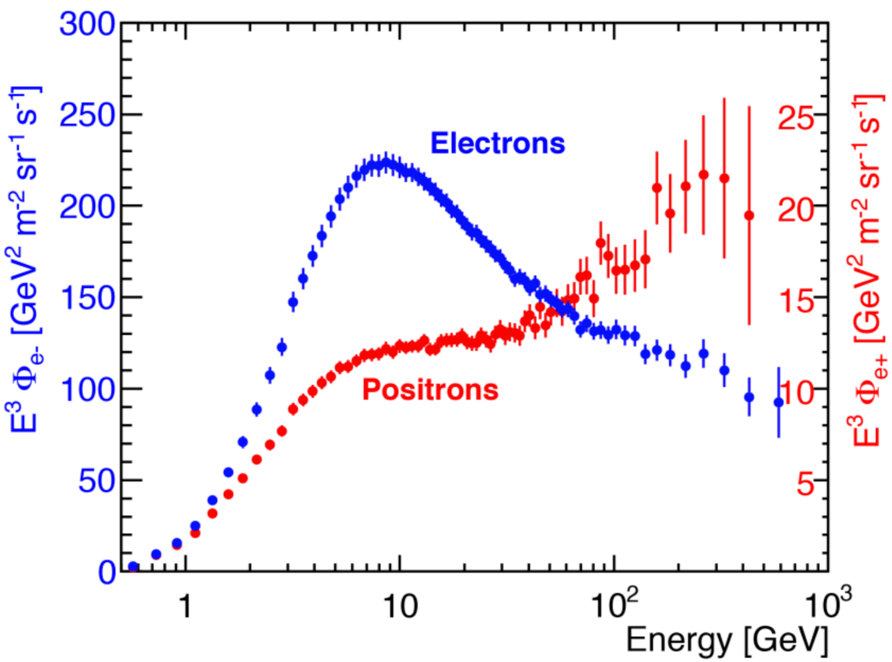
Key point here: this analysis is testing DM interpretation of Integral 511 keV data by comparing results to the non-observation of DM annihilation products ionizing the CMB.

From questions and discussions: what about cosmic rays?

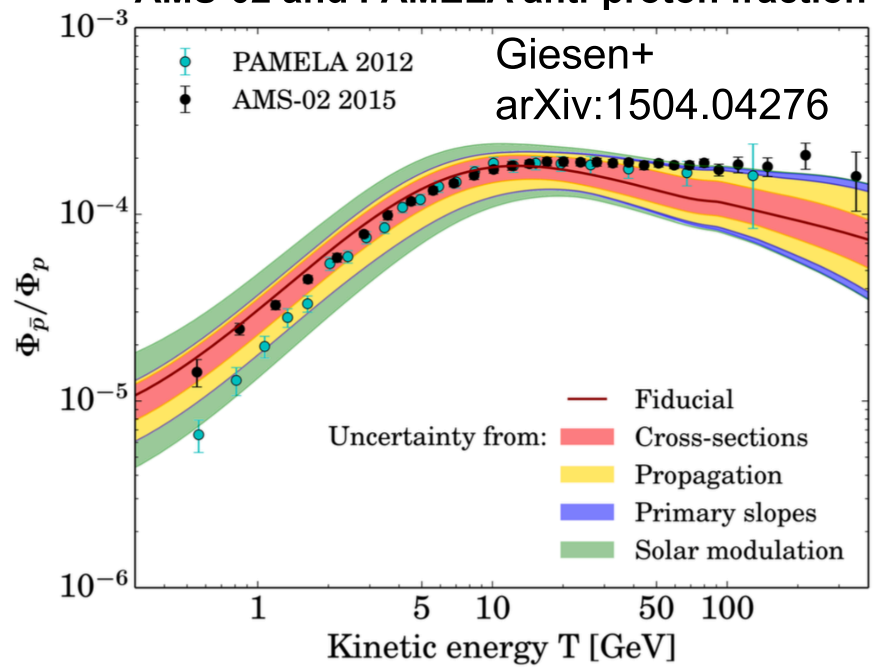


DM Limits from Cosmic-Ray Spectra

AMS-02 electron and positron fluxes

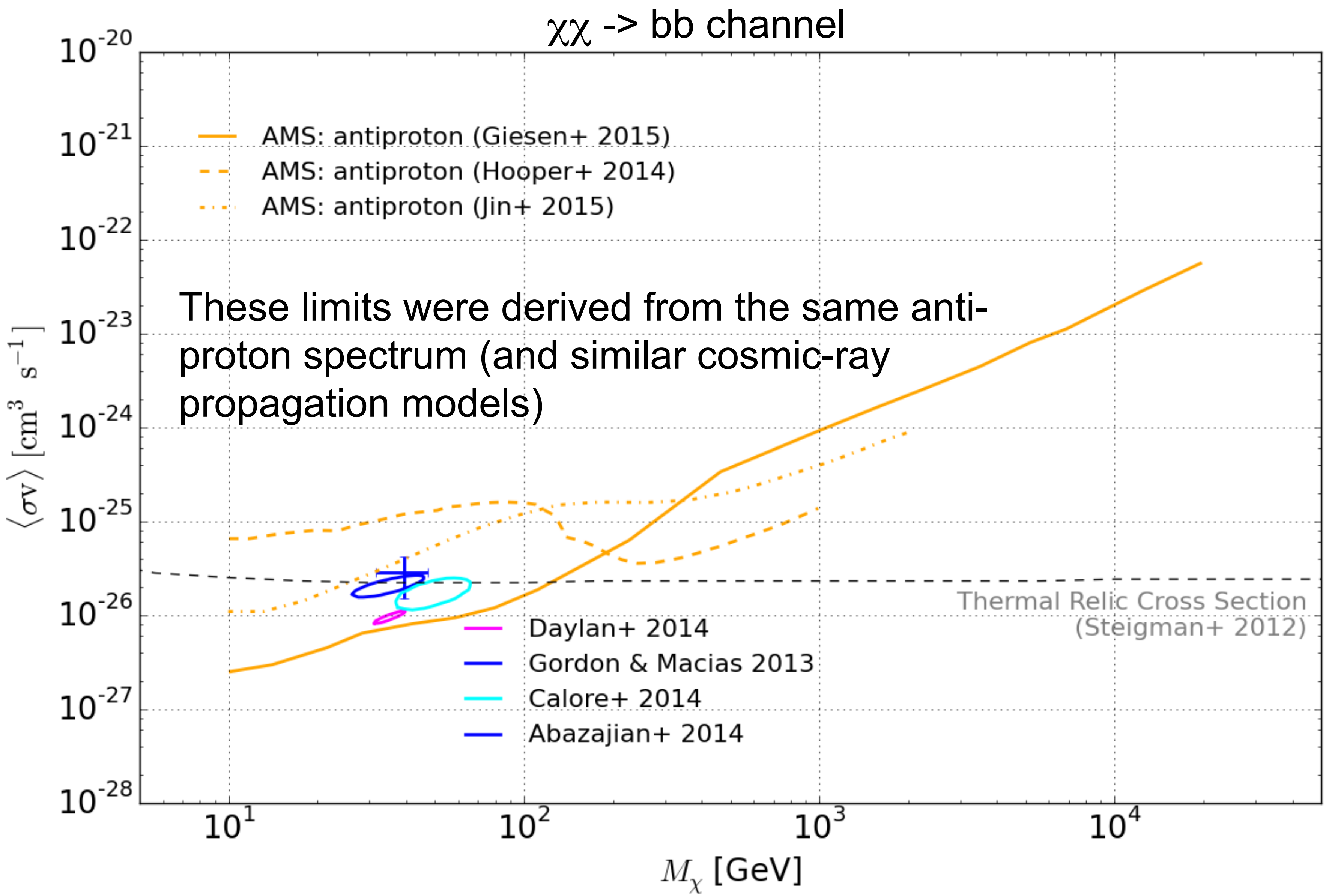


AMS-02 and PAMELA anti-proton fraction



- Extracting constraints on DM cross section from anti-particle fluxes requires detailed modeling of source populations, cosmic-ray propagation and other astrophysical effects (see sources of uncertainty on right figure).

Published Limits from Anti-Proton Spectra



The Good News

- No convincing (or even particularly compelling) DM signals in any searches: be they direct, indirect or accelerator-based
  - Some things that have been interpreted as signals are now strongly disfavored by other measurements (e.g., DAMA/LIBRA) or face strong competing hypotheses (e.g., positron fraction, Galactic center GeV excess)
- This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses
- Dark matter is more interesting that a simple ~100 GeV thermal relic WIMP

The Even Better News

- Many impressive efforts are underway:
  - to understand what the astrophysical data are telling us about the nature of dark matter
  - to continue to test the dominant WIMP paradigm by building more sensitive experiments and better understanding backgrounds
  - to develop ways to test other types of DM candidates
- This is a great application of the scientific method: we are finding ways of testing (and falsifying) hypotheses & developing new hypotheses
- We know that dark matter exists, perhaps we might be very lucky the discover that its particle nature is more interesting than, say, a ~100 GeV thermal relic WIMP from one of the simpler SUSY models

QUESTION: WHAT IF NATURE IS UNKIND AND DARK MATTER INTERACTIONS ARE NOT EASILY DETECTABLE?

OR

WHAT ELSE CAN WE LEARN ABOUT DM FROM ASTROPHYSICS?

Understanding the Astrophysical Nature of DM

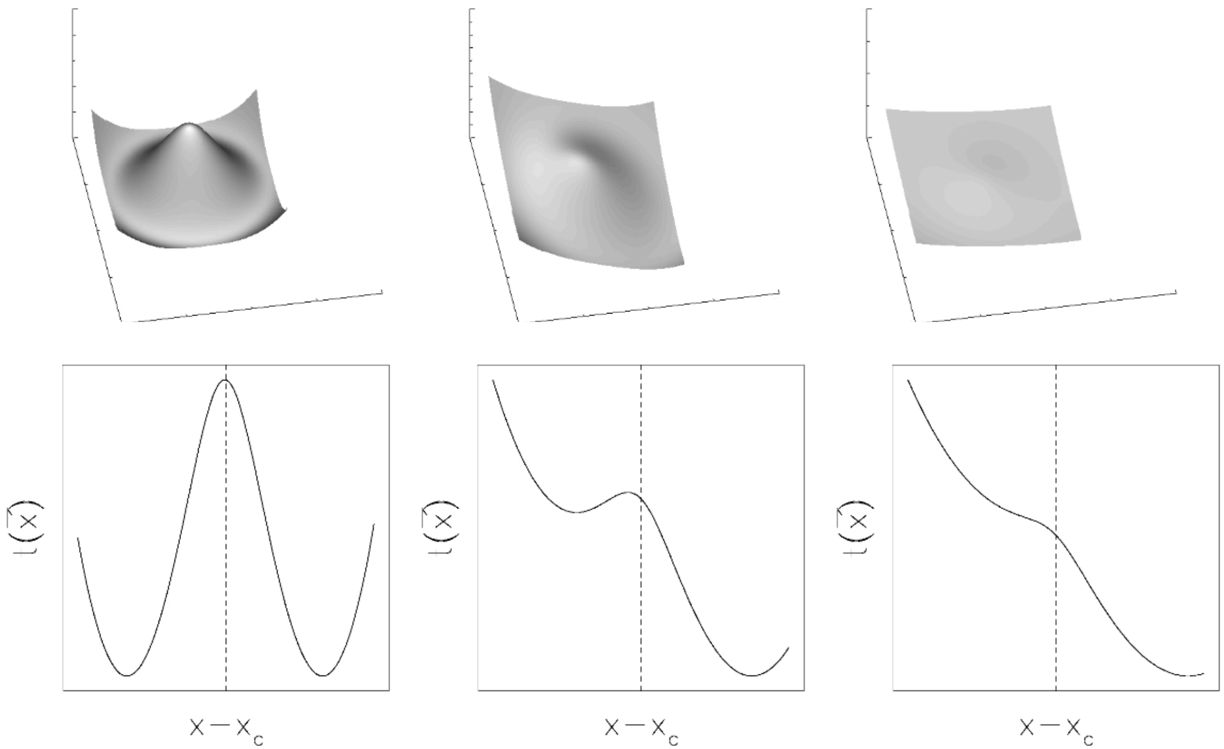
https://lsstdarkmatter.github.io/

cold dark matter warm dark matter

Lovell+ (2012)

- Wide-area surveys (DES, Pan-STARRS, Gaia, LSST) identify and characterize DM-dominated structures
- Modern numerical simulations improve our understanding of the dependence on cosmology, DM particle properties, “baryonic” effects in structure formation

Aside: Strong Lensing



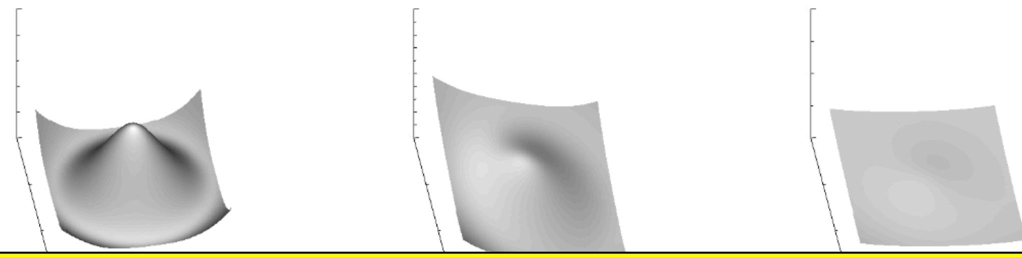
Einstein Ring   Einstein Cross   Weak Lensing

Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.

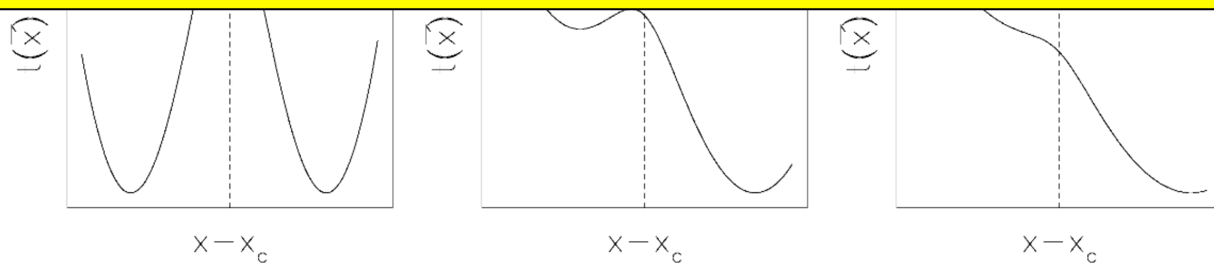
Aside: Gravitational Lensing

Gravitational time dilation means that light from lensed galaxy (behind) reaches us more quickly by travelling around the lensing galaxy (in front).

Aside: Strong Lensing



Key point for us: a strong lens creates a number of directions where the light travel time surface is flat: our sensitivity to lensing from sub-halos along these lines of sight is vastly improved



Einstein Ring Einstein Cross Weak Lensing

Light will appear for lines of sight where the gradient of the travel time is small: This includes minima, maxima and saddle points.

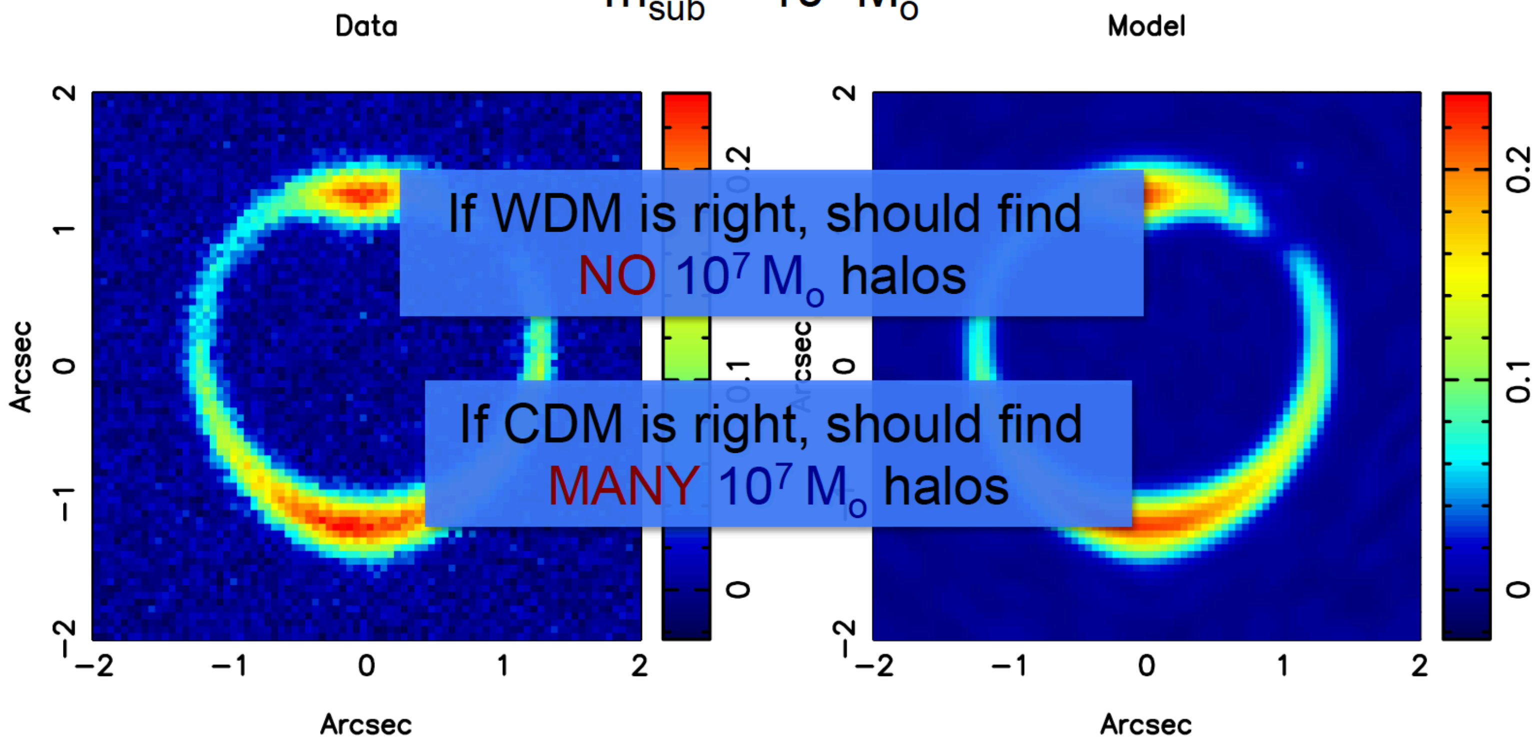
Measuring Strong Lensing Substructure Will Resolve CDM v. WDM

ICC University of Durham

Detecting substructures with strong lensing

Vegetti & Koopmans '09

$m_{sub} = 10^8 M_o$



If WDM is right, should find NO $10^7 M_o$ halos

If CDM is right, should find MANY $10^7 M_o$ halos

Can detect subhalos as small as $10^7 M_o$

Institute for Computational Cosmology

Other upcoming inputs from astrophysics

- Gaia is measuring proper motion and peculiar velocities of the stars in our galaxy and tracing out the Galactic gravitational potential
- Large scale surveys (DES, Pan-STARRS...) are finding new dwarfs and comparing properties to numerical simulations
- Gravity wave experiments are teaching us about the BH mass function and merger rate
- Neutrino astronomy is pushing observable horizon for high-energy events
- Cluster mergers / kinematics are teaching us about dark matter self-interaction rate
- Cosmology is pinning down the process of structure formation

Thank You